The Pennsylvania State University

The Graduate School

College of Engineering

Validation of the Modular Modeling System for Use in Accident Analysis at a Small-Scale Reactor Plant

A Thesis in

Nuclear Engineering

by

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ABSTRACT

The Modular Modeling System (MMS) was developed by the Electric Power Research Institute and the Babcock and Wilcox Company for the study of the thermal-hydraulic performance of pressurized water reactor plants at steady state and during some slowly varying transients. In order to determine the limits of transient severity that this code can endure, two experiments conducted at the Loss-of-Fluid Test (LOFT) facility at the National Reactor Testing Station in Idaho were simulated using the IBM/CMS computer of The Pennsylvania State University.

These experiments are a small break loss of coolant accident (Experiment L3-5) and an excessive steam generator load increase (Experiment L6-3). In the case of the former, the Modular Modeling System failed to accurately predict the performance of the LOFT facility. The MMS was, however, successful in predicting the significant thermal-hydraulic parameters of Experiment L6-3. The MMS predictions of the LOFT facility's performance during this experiment were more accurate than those of the more sophisticated RETRAN code.

This success validates the MMS' ability to predict the performance of nuclear power plants that are scaled much smaller than central station plants.

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Chapter 1

INTRODUCTION

Pressurized water reactor safety has been a key concern of environmentalists, various governmental agencies, electrical utilities, and reactor vendors since the beginning of the nuclear energy era in the 1950's. Today, with major nuclear accidents having occurred in both the United States and the Soviet Union, reactor safety is again at the forefront of issues driving the nuclear industry.

Fundamental to the issue of reactor safety is the ability to predict the performance of key plant operating parameters during both slowly varying transients and catastrophic accidents. These parameters can be separated into two general areas: core neutronics and system wide thermal-hydraulic characteristics. Thermal-hydraulics, in particular, is the focus of interest when a loss of coolant occurs from the primary volume of a pressurized water reactor (PWR). Thermal-hydraulics is the study of the the heat transfer and heat transport properties of fluid systems, and has been the focus of study of physicists and engineers for many years. These professionals have successfully reduced both core neutronics and plant thermal-hydraulics to a series of fundamental equations. Accident prediction work is based on these equations.

Although these fundamental equations are relatively few and simple, their use in reactor plant safety studies requires complex numerical methods for solution of the many resulting simultaneous equations. These complex numerical methods, in turn, require the use of computer codes written in today's modern languages to effect predictions within a reasonable amount of time, and with reasonable accuracy. The Babcock and Wilcox Company, in conjunction with the Electric Power Research Institute, has developed such a computer code, the Modular Modeling System (MMS). This code was not designed specifically to predict the performance of pressurized water reactors under accident conditions. Rather, it is intended for the early design stages and gross predictions of any large electrical generating plant, be it fired by conventional fossil fuels or a nuclear reactor. However, this code does have some features that make it very desirable for reactor plant accident studies. These features are its modularity concept and its fast execution time.

There are other computer codes that are suitable for reactor plant accident studies. Those that were designed specifically for reactor plant use include the many versions of RETRAN (developed by the Electrical Power Research Institute) and RELAP (Idaho National Engineering Laboratory), TRAC, and SIMMER (Los Alamos National Laboratory). For a variety of reasons, these codes are more

suitable for the in-depth investigation of reactor plant performance than is the Modular Modeling System. The expense required by their use, however, demands a cheaper alternative. Hence the Modular Modeling System became a candidate for the prediction of gross reactor system performance.

Because the MMS was designed for examining power plant performance in the steady states in addition to some small transients, it is logical to attempt to extend its use to include more severe reactor plant accidents that do not rapidly change the physical states being modeled by the simulation language.

In order to determine if the MMS indeed can be relied upon for accident analysis, its performance in predicting key reactor plant parameters in an actual accident needs to be known. Many accidents and unusual occurrences have happpened during normal operation of reactor plants in the United States. However, the instrumentation systems of the typical utility's power station are not designed to record the immense amount of data that is required for in-depth accident studies.

Other facilities have been established for the specific purpose of accident analysis, including the initiation of accidents on actual reactor plants. One such reactor plant is the Loss-of-Fluid Test (LOFT) facility at the National Reactor Testing Station near Idaho Falls, Idaho. This fully

operational reactor plant was designed and built specifically to provide a test bed upon which actual reactor plant accidents could be initiated and studied. These accidents range from small break loss of coolant transients without the nuclear core installed, to large break events that began with the core at 100 power. Because of the deliberate nature of the tests at the LOFT facility, instrumentation was in place that provided accurate records of the thermal-hydraulic characteristics of the plant throughout the various accidents. These records are the basis upon which the MMS can be evaluated as a useful code in accident studies.

Because the Modular Modeling System was never intended to model such severe transients as would occur in a large break loss of coolant scenario, an attempt to determine its ability to be used in large-scale accident studies would be doomed to failure. Instead, a smaller scale accident in which the parameter changes occur more slowly is the choice upon which such a determination could be made. Since many such accidents were performed at the LOFT, a selection of two of these experiments was used as the basis for this validation study.

Chapter 2

THE MODULAR MODELING SYSTEM

2.1 Objective

The Modular Modeling System was developed to provide

> an easy-to-use, flexible, economical, and accurate systems analysis code that can be used for simulating and analyzing the dynamic performance of nuclear . . . power plants.[1]

This effort was conducted primarily by the Electric Power Research Institute of Palo Alto, California. Other participants include the Babcock and Wilcox Company of Lynchburg, Virginia, and the Bechtel Group of San Francisco. Specifically, this system is intended for

- -specification, selection and integration of plant components
- -design and checkout of control systems
- -rapid simulation to expedite plant commissioning
- -best estimate plant safety analysis
- -procedure evaluation.[2]

These objectives were designed to fit the constraints of minimized computation time, minimized time for model development, and a reasonable amount of confidence in the generated results. The primary characteristic of the MMS included to meet these objectives is the modularity concept.

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[1] R. R. Dixon, S. W. W. Shor, and Lance P. Smith, The Modular Modeling System (MMS): A Code for the Dynamic Simulation of Fossil and Nuclear Power Plants (Palo Alto, California: Electric Power Research Institute, 1983), I, v.

[2] Dixon, Shor, and Smith, I, 1-1.

2.2 Modularity Concept

The current library of the MMS includes 64 modules. Most are designed to represent a typical component of an electric power generating station. These components range from the hydro-mechanical, represented by pipes and valves, to the electro-mechanical, represented by the on-off controller. The modules are divided into six basic groups which depend on power plant type. The fossil group includes component modules such as oil and coal fired boilers. The nuclear group includes reactors and steam generators. The controller group has proportional-integral signal generators, and the extended range group includes newer modules that allow for two-phase fluid flow. The balance-of-plant-component group includes pumps, pipes, and valves; components found at all power stations. Finally, the general group includes connections and junctions. This group is unique in that its modules do not always represent actual physical plant items, but are necessary to meet the connection requirements explained in the next sections.

The MMS modules have been designed to be joined together in a configuration which the user determines to best represent the actual physical system he/she wishes to simulate. In this joint configuration, all the physical properties the user wishes to calculate would then be determined by a FORTRAN computer program. This program,

generated upon completion of the module joining process, will perform its calculations based on the physical properties discussed in Chapter 1.

2.2.1 Module Joining

Each of the modules which simulates the containment of a flowing or static fluid is called a hydro-mechanical module. These modules are further sub-classified as resistive, storage, resistive-storage, or storage-resistive components. The fluid in these components is usually, but not necessarily, restricted to a single physical phase. Usually, either a liquid or a vapor phase is modeled. The vapor can be either saturated or superheated.

These modules must be joined in such a manner that the fluid "flows" alternately between resistive and storage nodes. The modules were designed so that adjacent modules do not solve for the same physical property, for example pressure, and no property is left undefined in a closed loop flow system. In system models that have open ended flows, the properties at the flow boundaries are maintained by user selected boundary conditions.

2.2.1.1 Resistive Modules

A module which uses a pressure drop as the basis of its flow calculations is described as purely resistive. A

typical example is a simple pipe. The arrow convention in Figure 1 shows that the inlet and outlet flow stream pressures, P, must be supplied as numerical input to resistive modules. The inlet flow properties are shown at the left of the figure, and the outlet flow properties at the right.

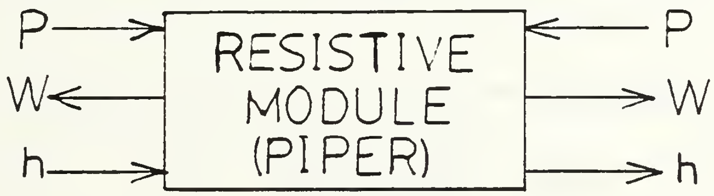

Figure 1: Resistive Module

The other input required is the inlet enthalpy, h. The arrows pointing out of the module indicate the calculated values delivered to the adjacent modules. These are the mass flow rates and the outlet flow enthalpy. Since resistive modules have no storage volume, the mass flow rate into the module must equal that flowing out.

2.2.1.2 Storage Modules

The continuity equation,

$$\frac{d\rho_e}{dt} = \frac{(w_e - w_i)}{V} \qquad \text{Eqn. 2-1}$$

is used as the basis of the storage modules. As Equation 2-1 and Figure 2 show, the inlet and outlet mass flow rates are needed as module input.

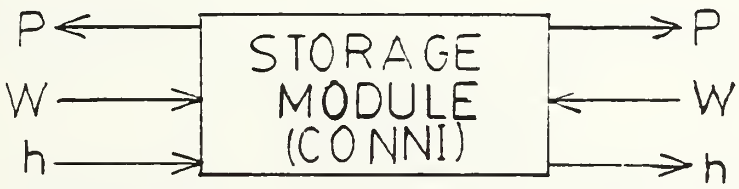

Figure 2: Storage Module

The primary output produced are, then, the inlet and outlet pressures. Of course, the other variables in the equation are assumed known. Such parameters as a tank volume, V, would be provided as input to the program. CONNI is the MMS name for a connective module.

2.2.1.3 Storage-Resistive and Resistive-Storage Modules

Modules that determine both pressure drops and flow rates combine the equations used in the purely resistive and storage modules into a single module. Such modules are

designated as resistive-storage or storage-resistive. A resistive-storage component is shown in Figure 3. Note that the inlet flow pressure, at the left of the figure, is by arrow convention a module input. This indicates the flow encounters the "resistive" section of the module first, and then the storage section. Simply reversing the P and W arrows would make this component into a storage-resistive type. UTSGR is a U-tube steam generator module.

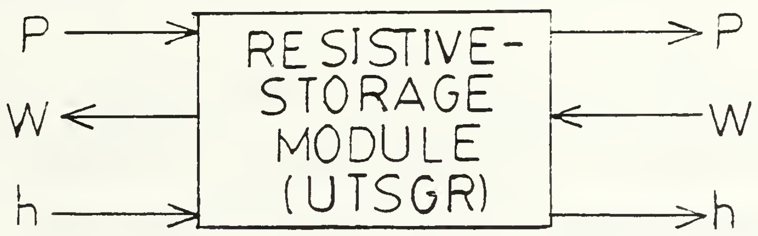

Figure 3: Resistive-Storage Module

2.2.2 Connectivity

Meeting the requirement that modules be joined in alternating resistive/storage fashion seems an easy thing to do. However, computing costs are very sensitive to the modules selected for use in the MMS, and hence the user must be very careful to select those modules which suit his/her individual requirements. Because the optimum configuration may require two resistive modules adjacent to one another,

seemingly violating the alternate resistive/storage requirement, still other modules were developed. These are appropriately termed connective modules. An example is a 10" pipe which is connected and constricted down to a 7" pipe. The connective module simply determines the missing pressure between the two resistive pipe modules. Since there is no envisioned configuration where two storage modules would be adjacent, there is no "connective" module of the resistive type to join them. All tanks, in reality, must be joined by a pipe (resistive module), no matter how short.

It is not required that the modules be connected in closed loop fashion. An open loop, or a closed loop with some inlet and outlet connections, is permissible. The models developed for this study are of the latter type. Any connections left open must be modeled by boundary conditions.

2.3 Physical Models

The physical phenomena upon which the MMS is based are listed in Table 1. These phenomena include some of the basic physical laws of thermal-hydraulics and heat transfer. All are applied to the appropriate modules, treating each module as a separate control volume.

Table 1: Basis of the Modular Modeling System

Phenomena	Basic Governing Equation
Conservation of Mass	$\frac{\partial \rho}{\partial t} = - \frac{\partial (\rho V_i')}{\partial x_i}$
Conservation of Energy	$\frac{\partial (\rho e)}{\partial t} = \frac{-\partial (\rho e V_i')}{\partial x_i} - \frac{\partial (p V_i')}{\partial x_i} + q''' - \dot{W} - \frac{\partial (\sigma_{ss} V_i)}{\partial x_i}$
Conservation of Linear Momentum	$\frac{\partial (\rho V')}{\partial t} = \frac{\partial (\rho V_i' V_j')}{\partial x_i} - \frac{g_c \, \partial p_i}{\partial x_i} - \frac{g_c \partial \sigma_{ij}}{\partial x_i} - \rho g(\sin \theta)$
Radiant Heat Transfer	$q = UA(\Delta T)$
Convective Heat Transfer	Dittus-Boelter Equation (other heat transfer equations are listed in reference [5])
Viscous Shear Losses	$\Delta h = \frac{fL}{D} \times \frac{V^2}{2g}$

The conservation laws are integrated around the surface of each module's control volume as the user directs. For example, he/she can include or ignore heat losses from a nuclear station's primary plant piping. To ignore these losses the MMS would simply integrate using the fluid boundaries into and out of a pipe module. To include these losses the pipe walls themselves would become part of the integration boundaries when performing the energy conservation calculations.

2.3.1 Liebnitz's Rule

In order to apply these physical laws to the thermal-hydraulic characteristics of an actual power generating system, a set of ordinary differential equations must be developed by the modules. This process makes use of Liebnitz's Rule to arrive at the integral form of the basic equation.

$$\int_V \frac{\partial \phi}{\partial t} = \frac{d}{dt}\int_V \phi \, dV - \int_S \phi V_S' \cdot d\hat{A} \qquad \text{Eqn. 2-2}$$

The left side of the Liebnitz Rule equation is the integral, over a given control volume, of the rate of change of a certain thermodynamic property. The right side of this equation is the form which must be set equal to the three phenomena of the conservation laws.

To illustrate the application of this rule, it will be applied to one of the conservation laws. The simplest

example is that of the conservation of mass. Converting Equation 2-1 to integral form yields

$$\int_V \frac{\partial \rho}{\partial t}\, dV = -\int_V \frac{\partial(\rho V_i)}{\partial x_i}\, dV \qquad \text{Eqn. 2-3}$$

which using the Liebnitz notation becomes

$$\frac{d}{dt}\int_V \rho\, dV - \int_S \rho V_S\, dA = -\int_V \frac{\partial(\rho V_i)}{\partial x_i}\, dV \;. \qquad \text{Eqn. 2-4}$$

The right or divergence term is converted to a surface integral using the divergence theorem,

$$\int_V \frac{\partial(\rho V_i')}{\partial x_i}\, dV = \int_S \rho\, V_i' \cdot d\hat{A} \qquad \text{Eqn. 2-5}$$

thus changing Equation 2-4 to

$$\frac{d}{dt}\int_V \rho\, dV = \int_S \rho V_S'\, d\hat{A} - \int_S \rho\, V_i'\, d\hat{A} \;. \qquad \text{Eqn. 2-6}$$

The left side of this equation is the change in the instantaneous mass in the control volume, dM/dt, and the surface integrals on the right reduce to

$$RHS = A_e \rho_e V_{se}' + A_l \rho_l V_{sl}' + A_e \rho_e V_e' - A_l \rho_l V_l' \;. \qquad \text{Eqn. 2-7}$$

Hence the conservation of mass can be written as

$$\frac{dM}{dt} = A_e \rho_e (V_e' - V_{se}') - A_l \rho_l (V_l' - V_{sl}') \qquad \text{Eqn. 2-8}$$

which contains no partial derivatives.

Similar developments, described in reference [5], are applied to the Conservation of Energy and the Conservation of Linear Momentum. These laws describe the "bulk"

properties within a control volume, properties that are termed extensive. Their equations alone are not enough to provide a solvable set of differential equations.

2.3.2 Intensive Properties

The remaining properties of the fluid needed to form a complete set of differential equations are labeled "intensive" properties. These include the specific density, temperature, and internal energy, and may have different values at the inlet and outlet boundaries.

2.3.2.1 Extensive/Intensive Property Relationship

To show the relationship between the intensive and extensive properties of each module, the average fluid enthalpy (intensive) and total internal energy (extensive) can be examined. In a control volume which has no heat transfer across its boundaries, the change in total internal energy is

$$\frac{dU}{dt} = w_e h_e - w_l h_l \qquad \text{Eqn. 2-9}$$

when there is no work done by friction. Using h as the average enthalpy within the the control volume, and M as the total fluid mass,

$$\frac{dh}{dt} = \frac{w_e h_e - w_l h_l - (dM/dt)h}{M} \qquad \text{Eqn. 2-10}$$

is the change in the specific enthalpy per unit time. Assuming that the change in h as the fluid flows through the module is linear, and that the inlet enthalpy is provided by the upstream module or is a boundary condition, then the outlet enthalpy is easily computed. Any instantaneous changes in the inlet property are mitigated at the outlet by assuming the derivative of the property leaving the node is equal to the derivative of the average value.

Forming a complete set of differential equations for each module is, then, a two step process. First, the extensive properties are used to determine average values of the intensive properties, and then these average values are used in the determination of the outlet flow intensive properties. These outlet values are then used as the input to the adjacent modules. For example, the derivative of the specific energy leaving the control volume becomes

$$\frac{dU_l}{dt} = \frac{1}{\rho V}\left\{ w_e h_e - w_l h_l + q - \dot{W} - p(dV/dt) - \bar{U}\rho(dV/dt) - \bar{U}V(d\rho_l/dt)\right\} \qquad \text{Eqn. 2-11}$$

after conversion to the intensive form.

2.3.2.2 The Complete Set of Thermal-Hydraulic Equations

The MMS uses enthalpy and pressure as the system states upon which its solutions to the sets of differential equations are based. The developers selected these properties because they are commonly used in many

engineering applications and to minimize numerical stability problems known to occur when basing models on density.

Selection of the equations used to solve for thermodynamic properties depends on one final factor, the number of fluid phases present within the control volume. In the case of a single phase, the equations are those developed above, one each for the conservation of mass and the conservation of energy. There are two differential equations and two unknowns, enthalpy and pressure:

$$\frac{dp_l}{dt} = \frac{1}{\alpha_p}\left\{\frac{1}{V}\left(w_e - w_l - \rho(dV/dt)\right) - \alpha_h(dh/dt)\right\} \qquad \text{Eqn. 2-12}$$

$$\frac{dh_l}{dt} = \frac{1}{\rho V}(w_e h_e - w_l h_l + q - W_s - \rho h(dV/dt) - hV(d\rho_l/dt) + V(dp_l/dt)). \qquad \text{Eqn. 2-13}$$

In these equations, the properties other than enthalpy and pressure are determined by FORTRAN steam property subroutines. The heat added to a control volume, q, requires a separate calculation using the heat transfer equations of Table 1. This separate calculation does not have any unknown values, but rather depends upon results from the previous time step, or boundary values.

Two-phase control volumes require the use of the "drift-flux" concept. "Using the drift-flux model and the assumption of inter-facial equilibrium between the steam and liquid phases, the separate phase equations can be combined

into a single set."[3] The use of two phases in a single volume introduces such variables as the quality, void fraction, and drift velocity. As the term "separate phase equations" implies, the approach is to treat each phase as a separate control volume within each module, and introduce other unknown terms that account for the "drifting" of mass and energy across the boundary from one phase to the other. The equations used are

$$\frac{\partial \rho_i}{\partial h_i}\frac{dh_i}{dt} + \frac{\partial \rho_i}{\partial p_i}\frac{dp_i}{dt} = \frac{1}{V_i}(w_1 - w_2) \qquad \text{Eqn. 2-14}$$

for the conservation of mass and

$$\begin{aligned}(\rho_i + h_i(\partial \rho_i/\partial h_i))h_i + ((\partial \rho_i/\partial p_i)h_i - 1/J_c)p_i = \\ \{f_1 w_1 H_1 - f_2 w_2 H_2 + (1 - f_1) w_1 H_2 - (q - f_2) w_2 H_{R2} + q\}/V \\ + A\{f_1 V_1 z_1 - f_2 V_2 z_2 + (1 - f_1) V_1 z_2 - (1 - f_2) V_2 z_R\}/V\end{aligned} \qquad \text{Eqn. 2-15}$$

for the conservation of energy.

In a two-phase storage module, the level of the liquid is determined using the average void fraction and the densities of the liquid and vapor.

2.3.3 Reactor Kinetics

The reactor modules available in the MMS use the point kinetics equations to calculate reactor power. These equations are

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[3] Dixon, Shor, and Smith, I, 3-16.

$$\frac{dn_i}{dt} = \frac{(1 - \beta)n_i}{\Lambda} + \sum_j \lambda_j C_{ji} + \sum_k \frac{D_{ik}}{\Lambda}(n_k - n_i) - n_i/l_i \qquad \text{Eqn. 2-16}$$

and

$$\frac{dC_{ji}}{dt} = \beta_j (n_i/\Lambda) - \lambda_j C_j. \qquad \text{Eqn. 2-17}$$

The number of groups of delayed neutron precursors varies with the module used. The third term on the RHS of Equation 2-16 accounts for the migration of neutrons from one node to another in the multimode modules.

Once the number of fissions occurring in an integration time interval has been calculated, the heat produced in the fuel is determined. This heat is then the basis for the change in enthalpy in each node using the system of differential equations described earlier in this chapter.

2.3.4 Other Physical Processes

The MMS accounts for the processes of viscous shear losses and heat transfer according to the basic equations listed in Table 1. The process of transport delay is accounted for by simple memory delays or by the use of multiple nodes (modules) to represent piping runs.

2.4 Integration

The MMS is based squarely upon the use of numerical integration techniques to solve the differential equations explained above. Each model creates a matrix of equations, the size of which is roughly proportional to the number of modules in the model. This matrix is solved for the unknown enthalpies and pressures at a fixed or variable time step. Once these new values have been obtained, calculations using regular FORTRAN statements and steam property subroutines are made to determine the new values of any other variables that may have changed. Such variables include tank levels, temperatures, and the extensive thermodynamic properties of each module.

Many algorithms have been developed through the years that can be applied to solving these sets of equations. The MMS, because it primarily calculates fluid mechanics and energy equations, generates a certain range of time constants. The inverse of these time constants are the system eigenvalues. It is the range of these eigenvalues that determines the optimum algorithm used to solve the differential equations. The algorithm used in this study is the Gear's Stiff.

The Gear's Stiff algorithm is a "variable step, variable order integration routine that is self-initializing."[4] This algorithm attempts to keep the size of each derivative in each time step below a preset value. If the size exceeds the set value, the time step is reduced and the set of equations is solved again. It also determines if the derivatives are approaching zero, and will increase the size of the time step if possible to minimize computation costs.

The time constants of power plants are in the 0.1 to 100 second range. The constants associated with the continuity equations are on the order of 0.01 seconds. This shorter time constant "stiffens" the process of solving the differential equations by implying the use of steps shorter than the user desires. Hence the term "stiff" is applied to the overall system. Simple Euler type algorithms must use the shortest time constant present as the time interval of the system solution and so would require about 10 iterations to advance even the smallest system time interval. Stiff algorithms make the assumption that the system's largest eigenvalues (shortest time constants) are always stable regardless of step size. This assumption can be made because the continuity equations are at quasi-steady state compared to the system time constants.

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[4] Mitchell and Gauthier, Assoc., Inc., Advanced Continuous Simulation Language (ACSL) User Guide/Reference Manual (New York: Mitchell and Gauthier, Assoc., Inc., 1981), p. 4-3.

In its current version, the MMS offers two "stiff" algorithms. The Gear's Stiff was selected because it will change the time step used in the solution many orders of magnitude, and so may possibly minimize CPU time.

2.5 Control Modules

Modules which perform control functions use simple comparative calculations to determine their output signals. For example, the on-off controller is in reality a simple switch with variable on and off setpoints. Other more complex controllers can have variable inputs and outputs which are determined by a series of polynomial equations. In this study, the most complex controllers used were the on-off type. The more complex versions were not required. Control modules do not contribute differential equations to the overall model's equation matrix.

2.6 Model Generation and Execution

To form and execute a complete MMS model, the designer follows the steps of Table 2.
Figure 4 shows the flow process of steps 6 through 11 in Table 2, which are performed by the user's computer. At The Pennsylvania State University, the MMS and its host language, the Advanced Continuous Simulation Language (ACSL), are available only on the CMS system.

Table 2: Model Formulation Process

1) Select the modules which best represent the system components needed to create a complete model.
2) Collect the information needed to complete the applicable parameter sheets of reference [5]. Sources include plant data and operating logs, and vendor specifications and drawings.
3) Determine the value of the initial operating parameters for use as boundary values.
4) Write an ACSL program, using the required MMS syntax.
5) Write an ACSL command file, using the necessary statements of reference [9].
6) Compile the ACSL program, locate and correct any errors discovered by the translator.
7) Correct any errors discovered by the FORTRAN compiler.
8) Create and load a FORTRAN module of the model.
9) Execute the module through one iteration to determine if any time derivatives exist that exceed allowable error criteria, and make needed corrections.
10) Execute the model to achieve steady state.
11) Execute any transients of interest.

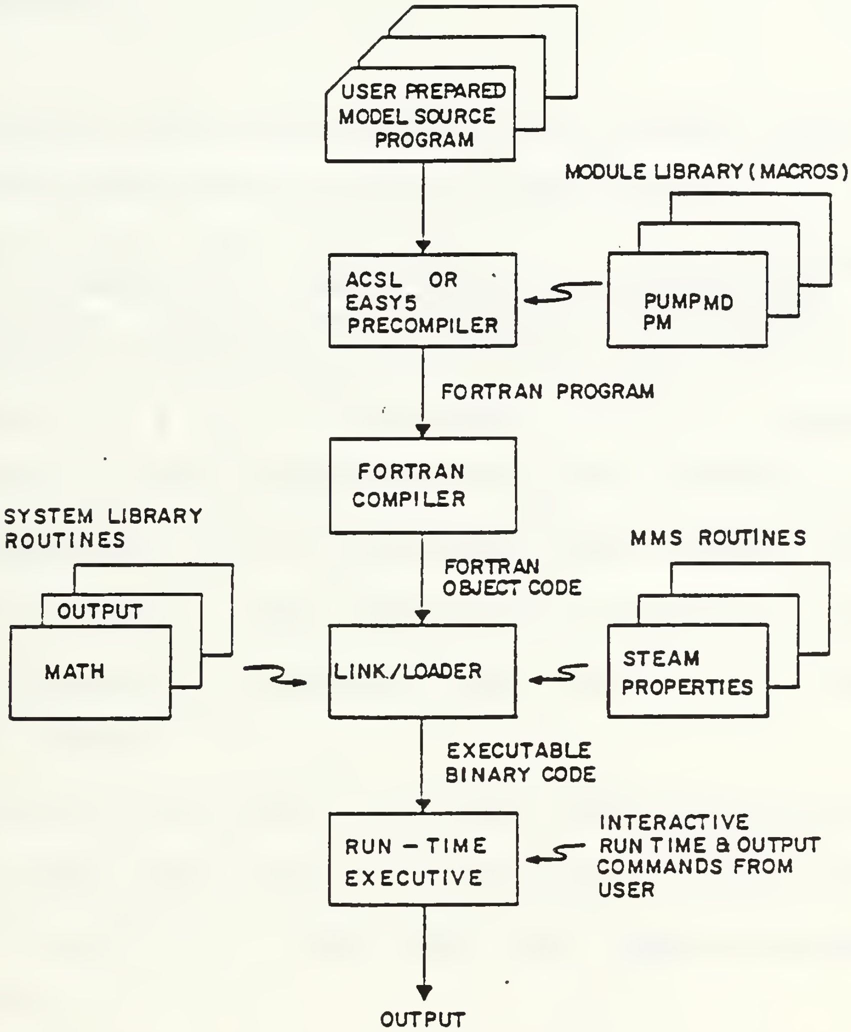

Figure 4: ACSL Flow Control

Chapter 3

THE LOSS-OF-FLUID TEST FACILITY

3.1 Objective

The Loss-of-Fluid Test facility was designed and built to provide the United States with a capability to

> simulate the major components and system responses of a commercial PWR during loss-of-coolant accidents (LOCAs) and during anticipated transients caused by abnormal PWR operations.[5]

The facility is a fully operational 50 MW(t) pressurized water reactor plant designed to simulate the major primary system components of a commercial sized nuclear power generating station. This facility was erected at the Idaho National Engineering Laboratory near Idaho Falls, Idaho, in the early 1970's.

In general, the intent in scaling the LOFT facility to a full sized PWR plant was to use the ratio of core power: 50 MW(t) to 3000 MW (t). This ratio was "used as extensively as practical."[6]

The LOFT facility was subjected to many transients, ranging from small break "mini-blowdowns" without the

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[5] Charles L. Nalezny, Summary of Nuclear Regulatory Commission's LOFT Program Experiments (Idaho Falls, Idaho: EG&G Idaho, Inc., 1983), p. 1-1.

[6] Douglas L. Reeder, LOFT System and Test Description (5.5-ft Nuclear Core 1 LOCEs) (Idaho Falls, Idaho: EG&G Idaho, Inc., 1978), p. 12.

reactor core installed to full-scale large break losses of coolant initiated at the reactor's maximum rated power.

3.2 Primary Coolant System

The primary coolant system removes the heat generated in the reactor core and transfers the heat to the steam generator, where it is passsed to the secondary coolant system. The primary coolant system also acts to contain any fission products that escape a fuel pin, and, with boron in solution, has a reactor control function. Nominal system pressure is 2250 psia, and rated flow at 100% power is 3,780,000 lbm/hr.

3.2.1 Intact Loop

The LOFT facility has a two-loop primary system, shown in Figure 5. This figure shows that only one of the primary loops contains a steam generator and operating primary coolant pumps. This loop, called the intact loop, simulates three of the four loops of a Westinghouse Nuclear Steam Supply System (NSSS). It can be used to simulate any actual NSSS' coolant loops which have not been opened in a Loss of Coolant Accident (LOCA).

Attached to the intact loop's hot leg (reactor outlet) is the pressurizer. This component's primary function is to maintain primary system pressure within the desired limits. The pressurizer is shown in Figure 6.

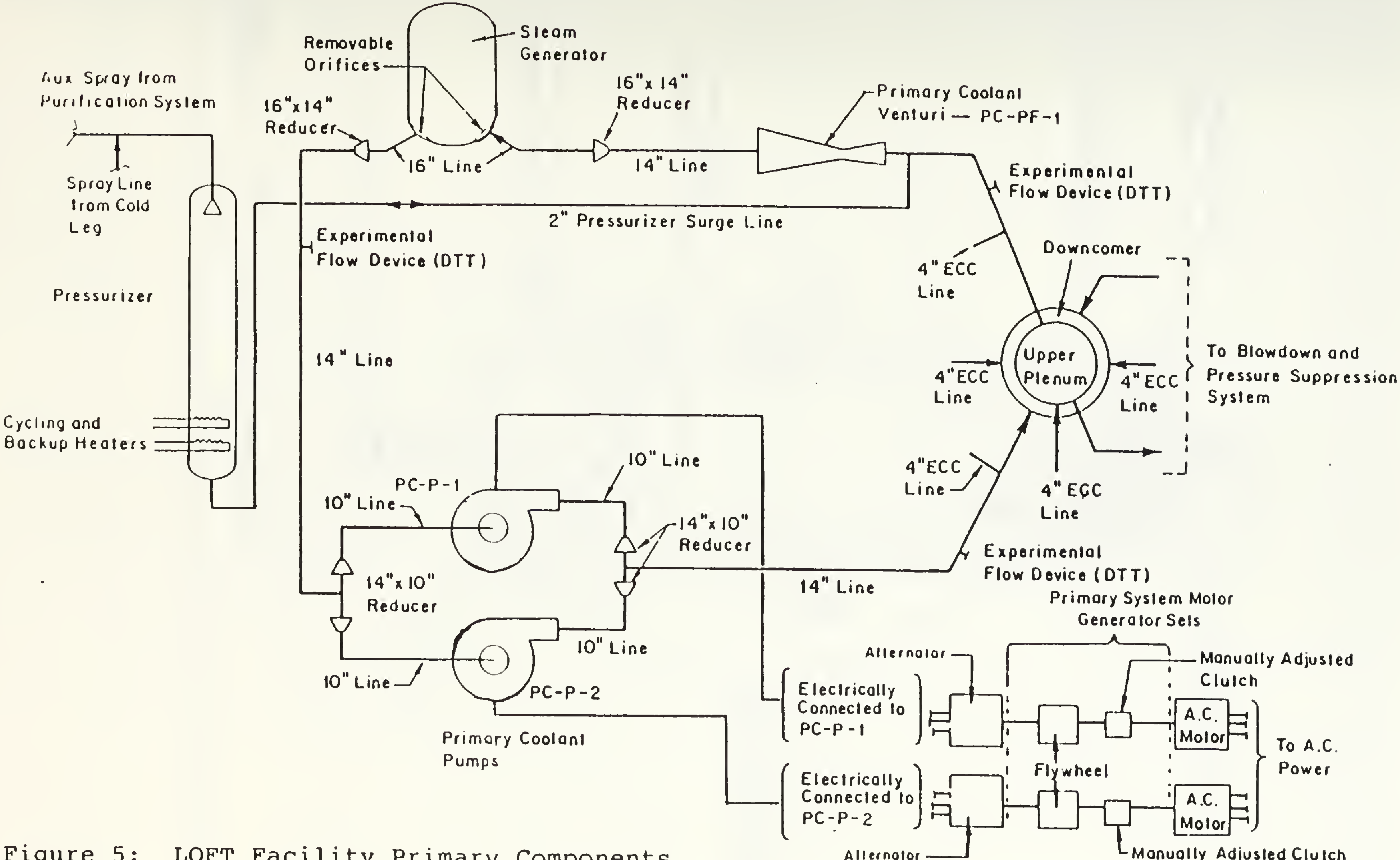

Figure 5: LOFT Facility Primary Components

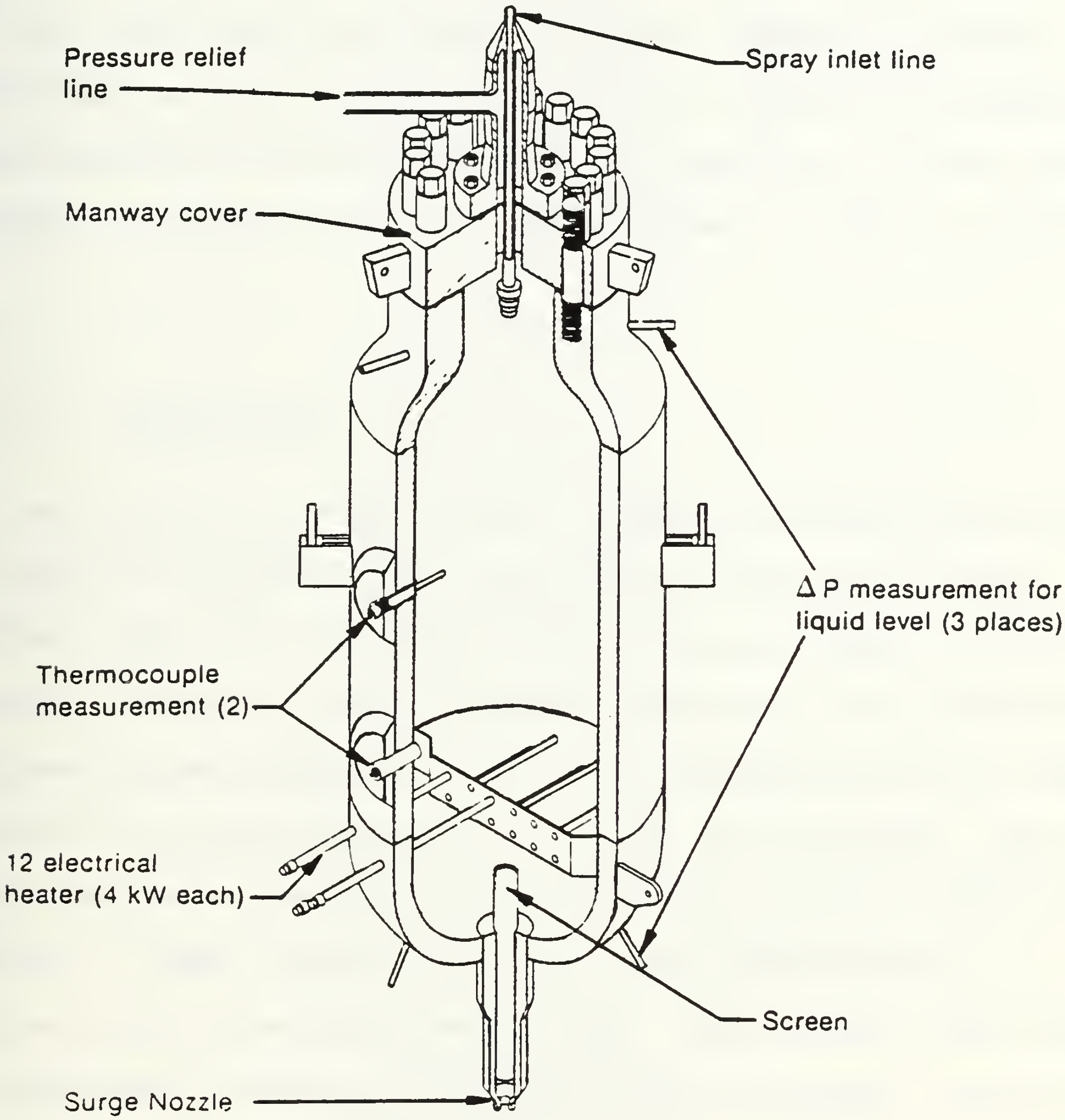

Figure 6: LOFT Facility Pressurizer

The steam generator is a vertical U-tube type (Figure 7), similar to full-scale steam generators at actual power plants.

The LOFT facility reactor coolant pumps are best described as the canned rotor, single stage centrifugal type, similar to the pumps found at commercial nuclear power plants. A cutaway of one of these pumps is shown in Figure 8.

3.2.2 Broken Loop

The facility's second loop is called the broken loop, and is used to simulate the large-scale losses of primary coolant that occur during a LOCA. This loop has no actual steam generator or coolant pumps. Instead, flow restricting devices called simulators create the pressure changes found across the steam generator and pumps in the intact loop. The other major components of this loop are the blowdown valves. These valves are of the quick-opening, hydraulically operated sleeve type. When opened, they act as the break location in a rapid loss of primary coolant experiment. The majority of the primary coolant system is constructed of 14" diameter stainless steel pipe.

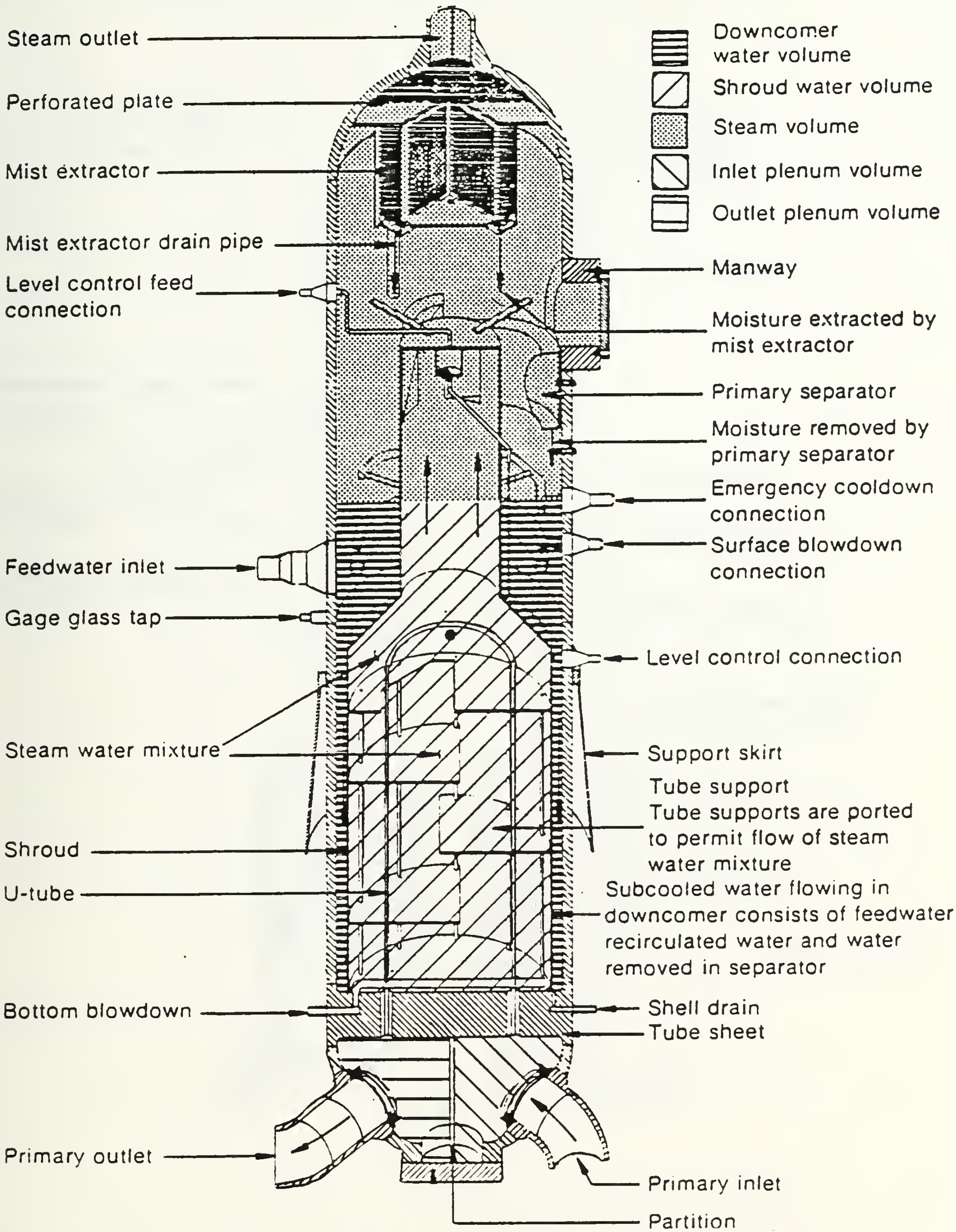

Figure 7: LOFT Facility Intact Loop Steam Generator

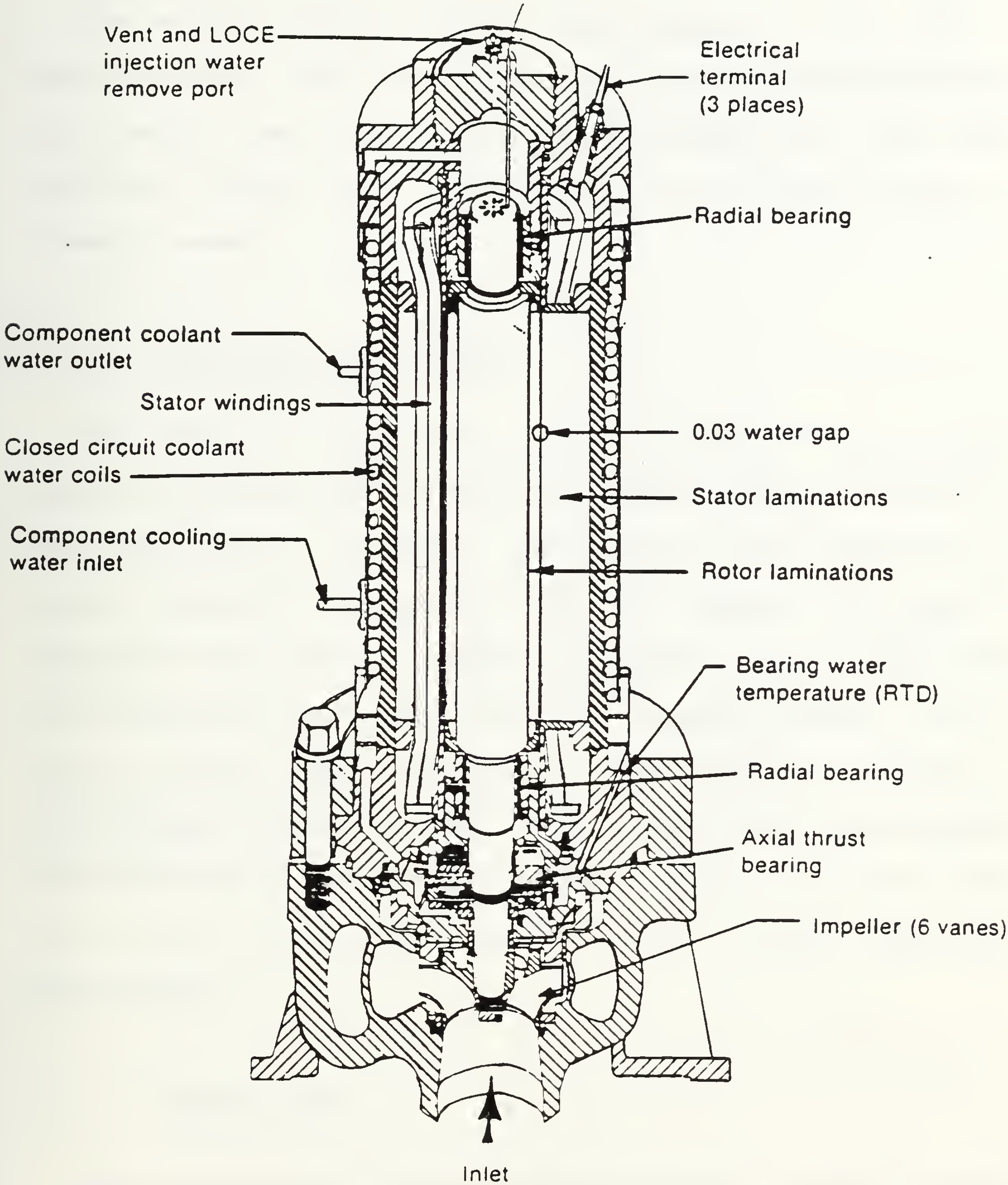

Figure 8: LOFT Facility Reactor Coolant Pump

3.3 Nuclear Reactor

The nuclear reactor is the heat source of the LOFT facility NSSS. Like the reactors of central power stations, this reactor has a cylindrical single pass core, with the inlet and outlet pipe connections near the top of the pressure vessel.

3.3.1 Structural Components

The reactor is contained within a 22 foot pressure vessel which is attached to the primary coolant loops as shown on the left side of Figure 9. This figure also shows the general internal arrangements of the reactor. The major components include the vessel's removable upper head and non-removable lower head, the core support barrel, flow skirt, and the upper and lower core support structures. These support structures act to hold down the core against the pressures of the passing primary coolant, maintain core and control rod alignment, and allow for thermal expansion and stresses.

3.3.2 Reactor Core

The core contains the uranium fuel used to power the LOFT facility's reactor. The core in place during the experiments of interest in this study was actually the

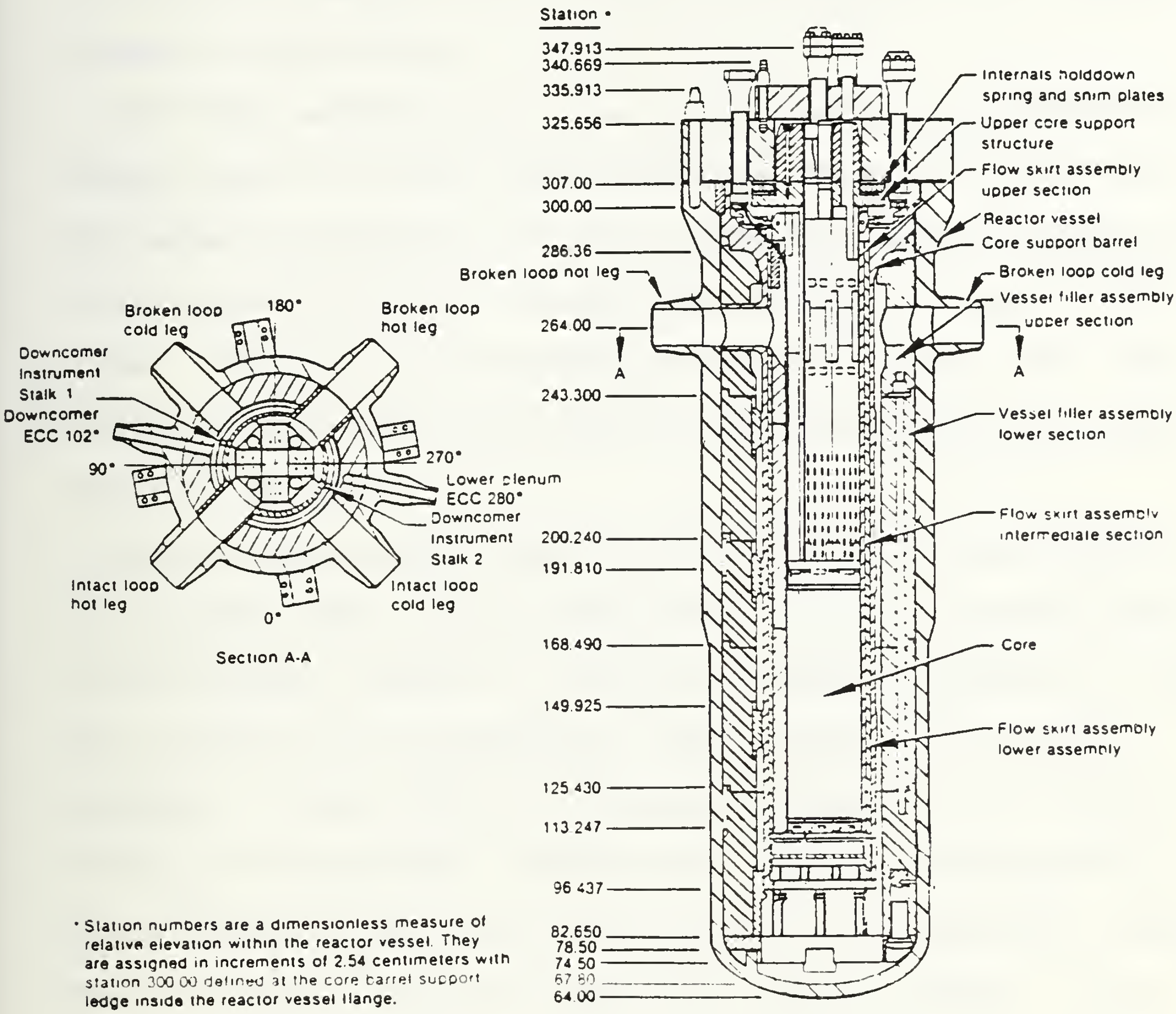

Figure 9: Cutaway View of LOFT Facility Nuclear Reactor

second used at the facility. This core is a modified cylindrical design with a length of 5.6 feet and a median diameter of 2.3 feet.

The fuel assemblies in the core closely approximate the design used in actual power plants. There are five 15x15 pin square assemblies and four triangular corner assemblies that contain 12 pins on each side, making a total of 1300 pins. The core is assembled as shown in Figure 10. The LOFT facility cores are rated at 2000 effective full power hours at 50 MW(t).

Neutron generation rates in the core are controlled by four spider type control rods and the use of soluble boron in the primary coolant. The control rods are located in the four square fuel assemblies that surround the center assembly. Their neutron absorbing materials are silver, indium, and cadmium. Because the LOFT facility core is small compared with the commercial cores it simulates, there was no need to devise a bank rod control system. The control rods all move at the same speed and time during normal operations.

3.4 Additional Primary Systems

3.4.1 Emergency Core Coolant System (ECCS)

In the transients examined in this study, changes in primary system pressure initiated emergency core coolant

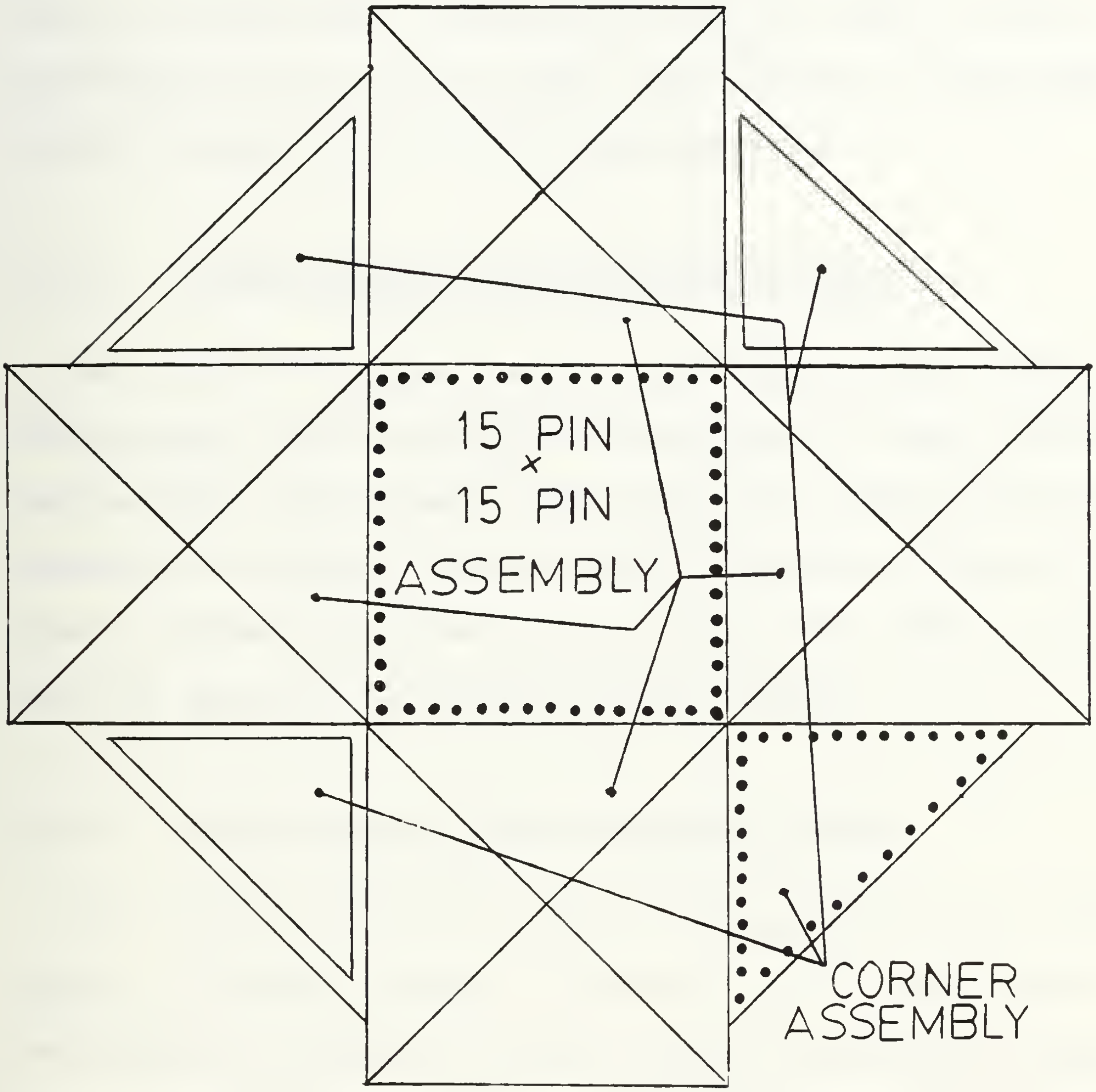

Figure 10: Reactor Core Arrangement

system operation. This system was designed for plant protection by ensuring the core would remain covered with liquid coolant after any size piping break, and act as part of a long term shutdown cooling system. Performance of these functions was intended to be as close to the performance of an actual ECCS, with safety of the LOFT facility being the overriding consideration.

3.4.1.1 High Pressure Injection System (HPIS)

The HPIS is designed to make up lost primary coolant during small and intermediate break events. This system has two positive displacement pumps and a nitrogen pressurized accumulator system to perform this function. Both act to inject borated makeup water into either the intact loop hot and cold legs, or the reactor vessel itself.

3.4.1.2 Low Pressure Injection System (LPIS)

The LPIS acts with the HPIS to mitigate the more severe losses of primary coolant. However, as its name implies, the primary system must be at a lower than normal pressure for the LPIS to operate. Such low pressures, if not accompanied by injection system operation, could lead to overheating of the reactor core in the worst case, or to the formation of non-condensible gases at the top of the primary coolant pump motor casings in a less severe case.

The principal components of the LPIS are two single stage centrifugal pumps. These pumps take a suction on the same borated water storage tank as the HPIS pumps, but have a much higher capacity, 300 gpm vs. 17 gpm at nominal discharge pressure. The borated storage tank has a capacity of 24,000 gallons, roughly 12 times that of the primary coolant system. The ECCS is shown in Figure 11.

3.4.2 Blowdown Suppression System

The Blowdown Suppression System simulates the backpressure effects of the containment structure of an actual NSSS, and collects the discharges from the primary piping during a fluid loss experiment. The major component is the blowdown suppression tank. This tank is a cylindrical vessel 38 feet long and 12 feet in diameter. It is connected to the broken loop by the blowdown suppression header and the quick-opening blowdown valves. There are other smaller connections to the primary piping, including one in particular to the intact loop cold leg that is important to this study.

In order to cool the large amounts of very hot water discharged from the primary system during an accident simulation, the blowdown suppression tank contains borated water at all times. The headers into the tank extend beneath the surface of this condensing pool. Additional cooling spray is also used during large break experiments to

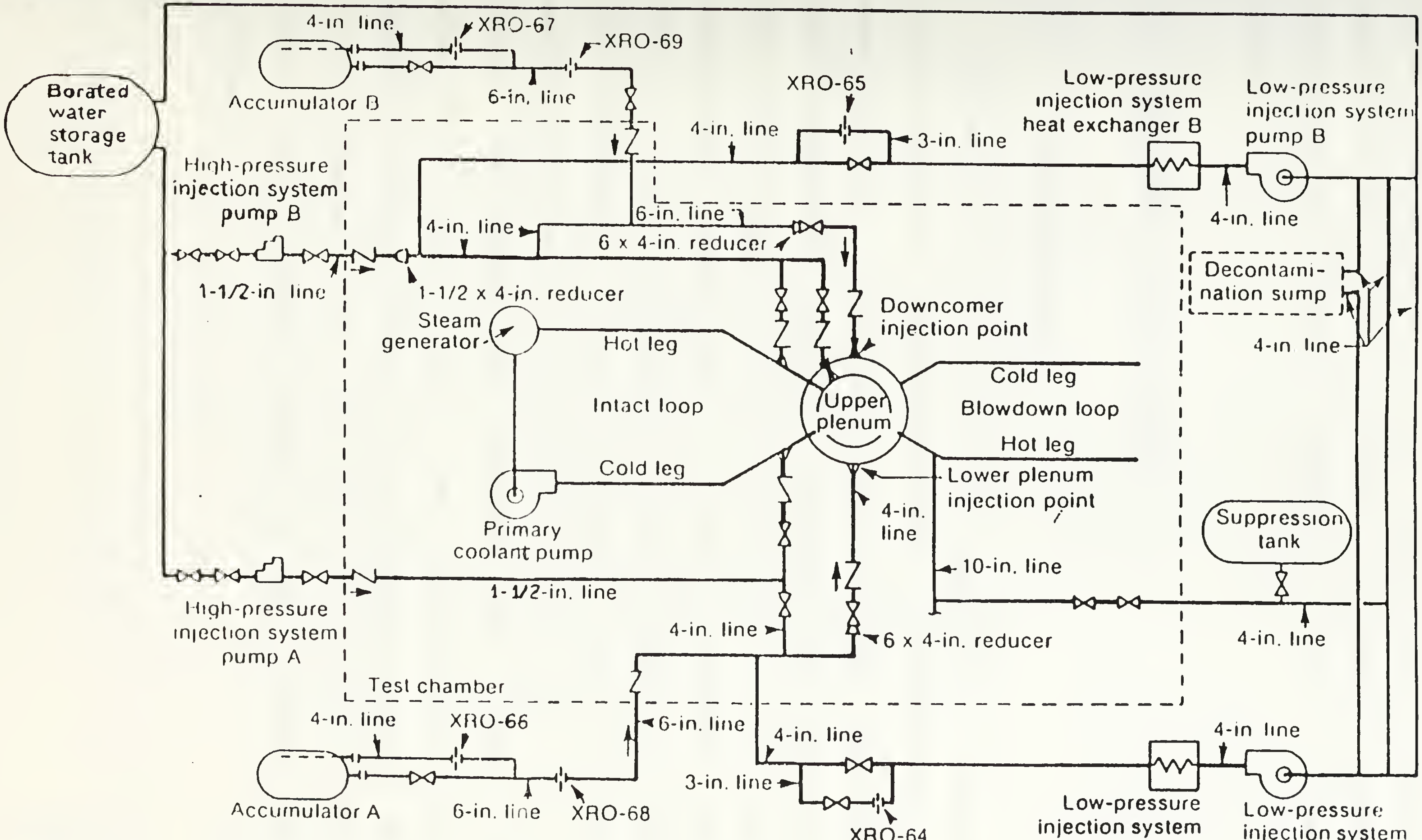

Figure 11: Simplified Piping Diagram of the ECCS

condense the steam in the tank. This form of tank pressure control is used to best simulate a containment building. A diagram of the blowdown suppression system is shown in Figure 12.

3.5 Secondary Coolant System

3.5.1 Steam Generator

The heat delivered to the steam generator by the primary coolant system is transferred across the U-tube walls to the secondary side. This heat serves to change the feedwater from a subcooled liquid to a saturated liquid-vapor mixture. This mixture has a quality of about 25% when the system is operated at rated power. The LOFT facility's steam generator uses two stages of driers to remove the moisture from the mixture: a swirl separator at the top of the tube bundle shroud and a mist extractor just below the steam outlet. The steam moves vertically out the top of the generator's 23 foot length. The steam generator delivers a maximum of 220,500 lbm/hr of dry saturated steam at 808 psia to the condenser. This flow rate is controlled by the steam control valve, located between the steam generator and the condenser.

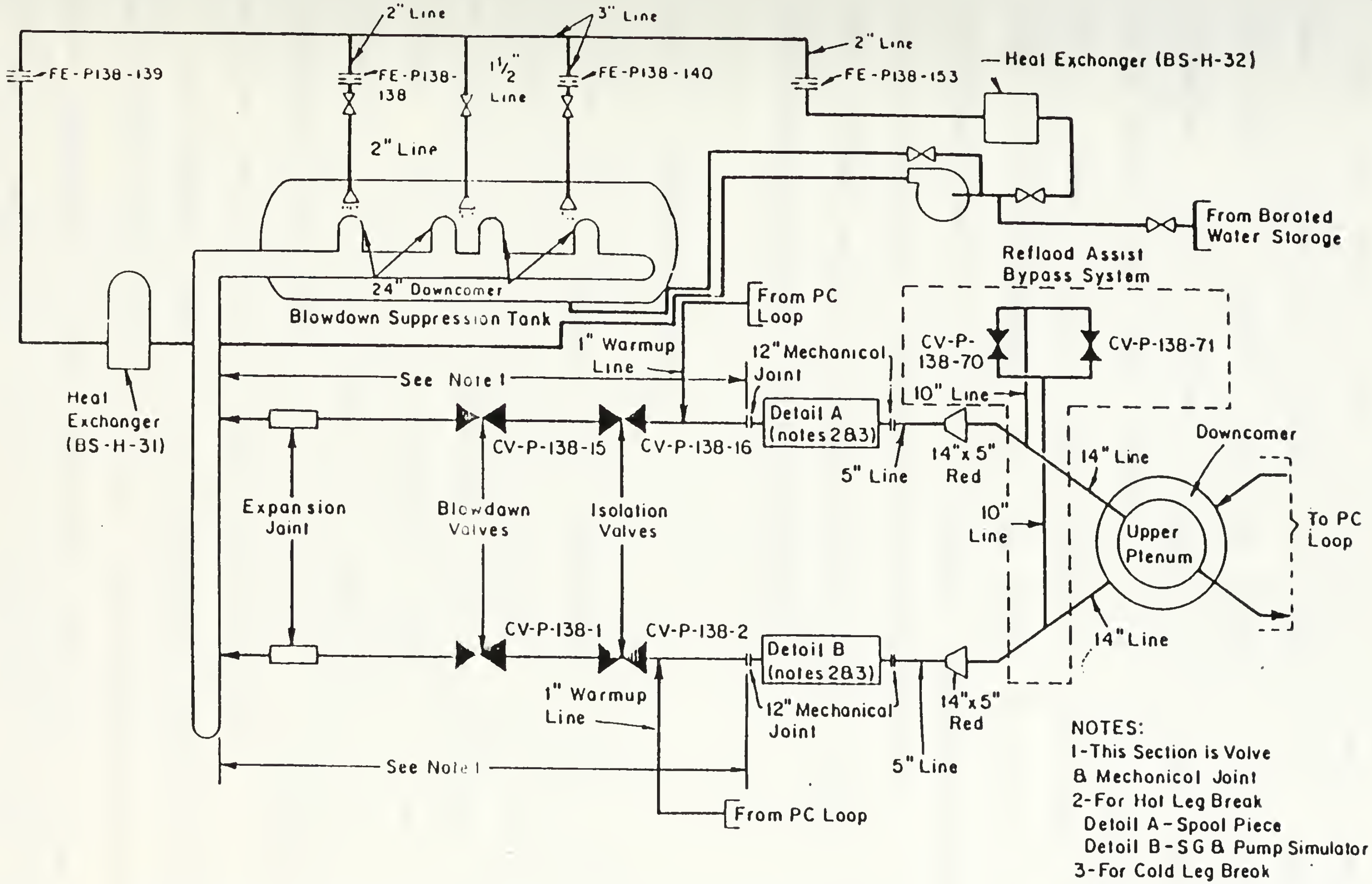

Figure 12: Simplified Diagram of the Blowdown Suppression System

3.5.2 Condenser

The LOFT facility does not use its reactor generated power to produce any energy in a usable form. Instead, all the energy is removed from the steam by an air cooled condenser. This condenser consists of finned tubes across which forced air flows, moved by a set of variable pitch fans. There is only a small pressure drop across the fluid side of the condenser, so the water arrives at the condensate receiver at very close to saturation temperature, 520°F, unless the air flow is such that there is a larger than normal amount of subcooling. The cooling air is discharged directly to the atmosphere.

3.5.3 Feedwater System

From the condenser, the condensate flows into a cylindrical vessel called the receiver. This vessel acts as an expansion/contraction volume for the secondary coolant system. From here the condensate moves to a water cooled subcooler. This subcooler is required to control the temperature and density of the water at the feedwater pump suction, and so prevent feed pump cavitation.

The feedwater pump is an electrically driven, multistage centrifugal pump which delivers the feedwater back to the steam generator via the feedwater regulating valve. The feedwater regulating valve is controlled by the steam

generator water level control system to match the steam flow rate with the feed flow rate and thus maintain the desired downcomer level in the steam generator. Also included as part of the feed system is an auxiliary feed pump which supplies a small amount of makeup water to the steam generator when the main pump is inoperative.

3.5.4 Design Theory

It should be noted that the LOFT facility's secondary coolant system is markedly different from that of an actual nuclear generating station. The facility has no turbines, water cooled condensers, or electrical generators. This equipment is not needed because the primary intent of the facility is to examine the primary system performance under accident conditions. This unusual design makes modeling the facility's secondary system on a direct component by component basis impracticable because an air cooled condenser module has not been developed. However, some substitutions and omissions can be made to create a suitable working model. Figure 13 is a simplified schematic of the secondary coolant system.

3.6 Instrumentation

Because the LOFT facility was designed for research, it was constructed with an extensive array of instrumentation

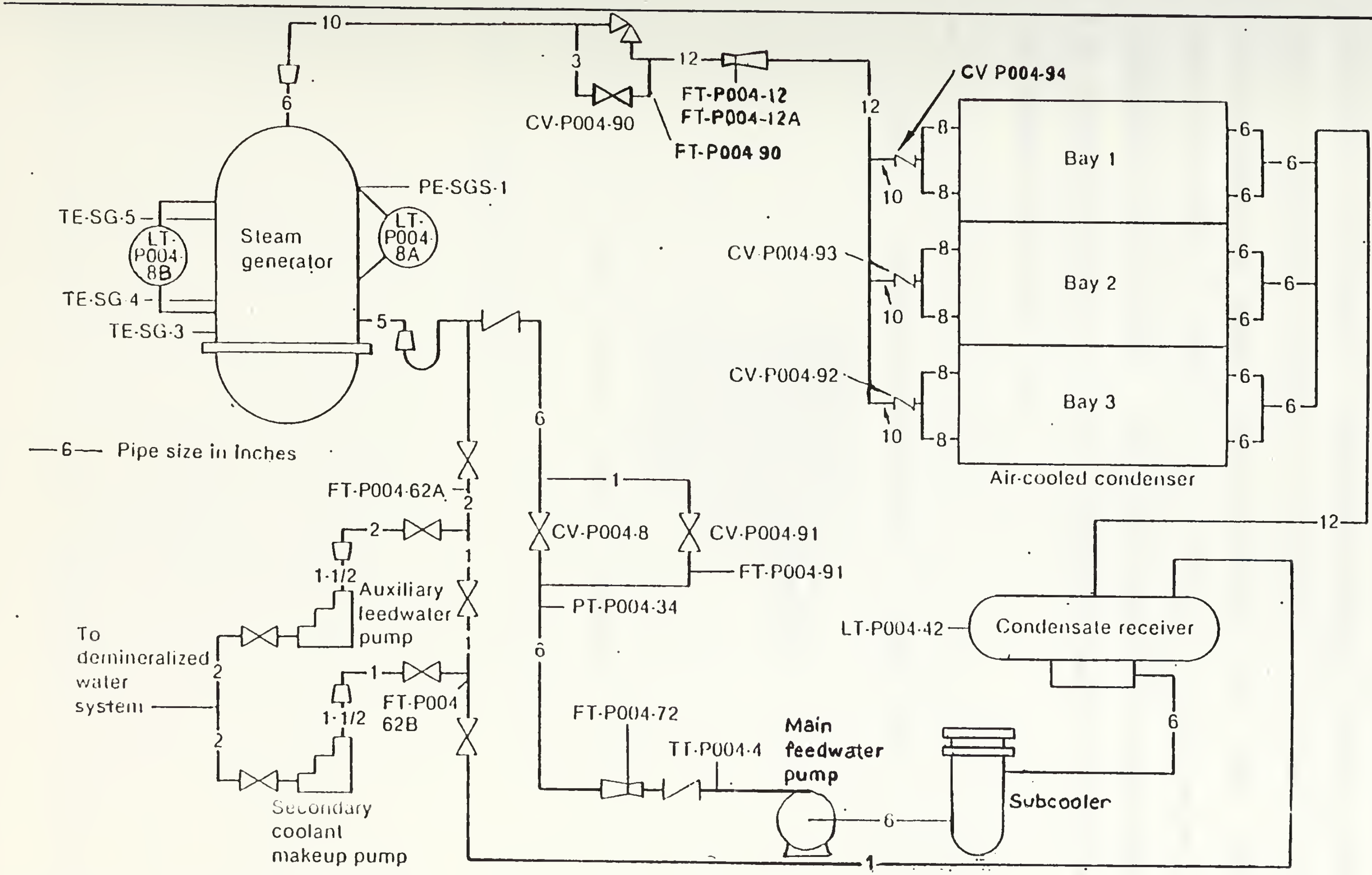

Figure 13: Secondary Coolant System Piping Diagram

which uses fixed and movable detectors that monitor the parameters in Table 3. Typical nuclear industry devices such as resistance temperature detectors, and not so typical devices such as gamma densitometers, are used. The measuring devices numbered over 450 during the experiments examined in this study. Only the output of those which met the accuracy criteria of the testing directors are used in the comparisons made later.

Table 3: Parameters Measured at the LOFT Facility

- temperature
- absolute pressure
- differential pressure
- material stress
- liquid level
- fluid density
- flow rate
- pump speed.

Chapter 4

MMS MODEL DEVELOPMENT

4.1 Development Process

In order to create a model which suits the purposes of the systems analyst, it must first be decided which specific parameters he/she desires to examine. In this study, the parameters of interest include the temperature, pressure, and enthalpy at various points in the primary coolant system, and the temperature and pressure in the steam generator secondary side. These were chosen because the experiment reports included these parameters. Further, these parameters provide easy to interpret system performance factors which a person familiar with pressurized water reactor operations will understand.

4.2 Parameterization

Once a module was selected for use in the LOFT facility model, the next step was to assemble input data which best describes the actual component. Collecting the necessary information required the use of many description documents and experiment reports. Each module used in the model required its own sources of information, and a set of calculations performed per the requirements of reference

[5]. The following sections describe the module selection process and the references used as sources for input data.

4.3 Module Selection

With the parameters of Section 4.1 in mind, module selection became a relatively (compared to the parameterization discussed later) simple process. The criteria of selecting a module to represent an actual LOFT facility component now depended on what types of conditions a module was designed to simulate, and if those conditions were to be encountered in the transients used in this study.

4.3.1 Major Components - Primary System

The major components of the primary system include the reactor, steam generator, primary coolant pumps, and pressurizer. These were each selected based on the criteria presented in the module descriptions in Volume III of reference [5]. There are at least two modules available to represent each one of these components. In the transients used in this study, the LOFT facility's broken loop was not utilized, and so is not part of the models. Instead, a single primary coolant loop was created.

4.3.1.1 Nuclear Reactor

The current version of the MMS has four pressurized water reactor modules. The primary difference between the four is the number of core nodes used in solving the reactor kinetics equations. The simplest modules, RX1 and RX1XR, use a single node; RX3 uses three cylindrical stacked nodes; RX12 divides these three cylinders into four quadrants to provide twelve nodes. The RX1 module was designed for those transients which occur over periods of minutes and hours. Since decay heat plays a major role in the transients used in this study, it appeared that RX1 would not accurately predict the heat added to the primary coolant system after reactor shutdown. On the other hand, since most of the plant performance examined occurred immediately after a reactor shutdown, the more complicated set of twelve node kinetics equations was not considered necessary. Hence the module decided upon was RX3, a storage-resistive module. This module's kinetics were expected to be accurate enough for the short time the reactor was at power, and its decay heat calculations are the same as those of RX12.

A feature of this module, natural circulation, also figured to be of use because in one of the transients examined the reactor coolant pumps were shut off.

Input parameters for this module are the most complicated of any used in the LOFT facility model. Data from references [1], [3], [8], [9], and [12] were used to compile

the parameters and tables. Since the RX3 has two hot leg connections and four cold leg connections, identical to a Babcock and Wilcox two loop plant, one of the hot legs in the model was simply blocked with a boundary condition of zero mass flow. The cold legs, however, do not allow a zero mass flow rate because they input to the storage part of this module. Instead, the incoming cold primary flow was divided into four parts, one for each of the four RX3 cold legs.

The name used for the reactor module in the LOFT facility model is RXX. Key internal variables include YRXX, ZATRXX, GBOR, and ZLHRXX, which are the rod heights, core power, boron concentration and upper plenum enthalpy, respectfully. Although the RX3 module allows for five rod banks (YRXX is a subscripted variable), at the LOFT facility the four actual control rods move as a single bank. Hence all five values of YRXX were initially assigned the same value to simulate the single LOFT facility bank.

4.3.1.2 Steam Generator

There are five steam generator modules available in the MMS, one once-through version, and four U-tube versions. Since the LOFT facility steam generator is of the U-tube design, the once-though module was obviously not appropriate for use.

Of the four U-tube modules, one, UTSG, is a low order version. Low order versions are intended to be simple and relatively inaccurate to save on computation costs. Since the transients examined in this study involve large pressure changes on the secondary side of the steam generators, the low order module was originally not selected. Of the remaining three versions, two are intended to serve similar functions: UTSGR and UTSGA. The latter is a newer, unproven module, while the former is an unimproved version of the first U-tube steam generator module created. Improvements to UTSGR have been recommended by various users of the MMS, but have yet to be incorporated. The final version, UTSGE, includes feedwater preheaters that the LOFT facility does not have.

For the reasons just explained, none of the U-tube steam generator modules were completely satisfactory for use in the LOFT facility model. Therefore two of the four modules available were selected to allow a wider range of MMS performance. One transient was examined using UTSGR to see if indeed the performance was as poor as expected. UTSG was used for the second transient to determine if "low order" is a term that applies only during use in predicting extremely violent transients.

These modules model the natural circulation of an actual steam generator, heat storage in the metal mass, and heat transfer by both subcooled and bulk boiling, but to varying

degrees. By its nature, the low order module uses a much simpler set of equations. All of these characteristics were used to predict the performance of the LOFT facility under accident conditions. Both modules use the drift-flux method described in Chapter 2 to calculate the two-phase flow in their riser sections.

UTSGR divides the U-tubes into four different heat transfer regions: hot and cold leg subcooled heating, and hot and cold leg bulk boiling heating. Different heat transfer equations are used, depending on the type of heating and temperature differences. The least amount of heat is transferred in the cold leg subcooled region because of the minimized temperature differences between primary and secondary fluids, while the most heat is transfered in the subcooled hot leg region because of the large temperature difference. UTSGR is a resistive-storage module on the primary side, and simply a storage node on the secondary side.

UTSG uses a much simpler scheme for calculating the rate of heat transfer. Only two regions are used, one subcooled and one bulk boiling. Further, the sizes of these regions are fixed, while in the UTSGR the region sizes vary with the recirculation ratio.

Both of these modules carried the named ITL for this study. This name was selected because the only steam generator at the LOFT facility is in the intact loop. In

contrast to UTSGR, UTSG is a storage-resistive module on the primary side. Key parameters calculated by this module include the downcomer mass and mass flow rate. UTSGR also calculates a downcomer level.

4.3.1.3 Reactor Coolant Pumps

The MMS has two pump modules, PUMP and PUMP4Q. PUMP can be powered by a variety of external sources including a steam turbine and electric motor. Since the LOFT facility coolant pumps are driven by electric motors, this module would seem to be useful in this study. However, PUMP was designed to operate only in the positive differential pressure, positive flow region of the its operating characteristic curves.

The PUMP4Q module does not have the option of an external power source. It does, however, simulate operation in all quadrants of the pump characteristic curves. Since one of the LOFT facility experiments used in this study included a shutdown and coastdown of the reactor coolant pumps, this module was selected. Another useful feature of this module is that it can simulate two or more identical pumps in parallel without having to use a separate module for each. The name used for this module in the model is RCP, for reactor coolant pumps.

Determining the input parameters of this module was difficult because not only were the volume and other

physical dimensions needed, but the actual pump's four quadrant operating curves were needed for input as tabulated data. Fortunately, this data was available in reference [12].

4.3.1.4 Pressurizer

Of the four pressurizer modules available in the MMS, one could not be used because it is a low order version which does not continue operation when empty. The other three have similar characteristics, so the module settled upon was PZRB. This module is similar to one which was proven reliable in reference [6]. Implementation of this module was simply a matter of converting from the full-scale pressurizer physical parameters provided in the default to the much smaller dimensions of the LOFT facility pressurizer. The name used in the model for this module is PZR.

The pressurizer modules are unique among those which carry fluids because they have three instead of two mass flow connections, one each for the surge line, spray line, and pressure relief line. Module operation ranges from nearly solid conditions to empty, a useful characteristic for studying reactor plant accident behavior.

Key internal variables of PZRB are ZLSPZR, ZMLPZR, ZHTPZR, and ZWBPZR. These are, respectfully, the liquid level, liquid mass, electric heater power, and mass flow rate from the vapor to liquid regions.

4.3.2 Balance of the Primary Coolant System

The remainder of the primary coolant system includes two pipes, the surge connection, four valves, and two connective modules, depending on which steam generator module is used.

4.3.2.1 Pipes

To ensure proper loop flow time delays from the steam generator to the reactor and back to the steam generator, a flow resistive pipe was placed between the reactor outlet and steam generator inlet (with a pass through the surge junction), and from the steam generator outlet to the reactor coolant pump suction. The latter pipe was not included with the UTSG steam generator because of the reversed location of the storage and resistive parts of this module compared with UTSGR. Instead, another hot leg pipe located between the surge connection and the steam generator primary coolant inlet was required. This module is named SSG, for surge to steam generator connection. When UTSG is used, the volume of the hot leg pipes is increased as required to account for the entire volume of all piping. Proper accounting for the correct volumes is expected to ensure proper pressure calculations.

The hot leg pipe is called RXO for reactor outlet.

4.3.2.2 Surge Junction

The surge junction acts as a storage node to the flow from pipe RXO into the primary side of the steam generator, and as a resistive node to the flow into and out of the surge connection of the pressurizer. Although very little energy is lost or gained in this node, a separate surge module was developed for the MMS and is used in the LOFT facility model to account for the large reactor coolant flow, much smaller surge flow, and to provide a resistance to keep the pressurizer from completely emptying into the rest of the primary loop during an up-power transient. Normally, at least two separate modules would be required to allow bi-directional flow.

4.3.2.3 Valves

The four valves used in the primary coolant model are the pressurizer spray valve, PSY, the pressurizer safety relief valve, REL, the high pressure injection stop valve, XC, and a valve, BRK, which represents a connection between the cold leg and the blowdown suppression tank.

There is a pipe, with a gate valve, on the actual LOFT facility cold leg piping downstream of the reactor coolant pumps. It is connected at its other end to the blowdown suppression tank. Flow through this connection is required in one of the transients examined in this study. In the

LOFT model only the valve is required. The downstream side of the valve has simply a boundary condition, a constant pressure which was varied during model execution from 14.7 to 500.0 psia. The need for BRK will become apparent in Chapter 5.

The spray control valve PSY connects the primary coolant pump discharge to the vapor space of the pressurizer. It is an automatically controlled, quick opening valve both at the LOFT facility and in the MMS model.

REL connects the pressurizer vapor space to the blowdown suppression tank at the LOFT, but simply discharges to an infinitesimally large tank in the LOFT facility model. The pressure in this "tank" is a constant 14.7 psia by use of a boundary condition. Verification of the use of this number was not made because in the transients of this study, no significant pressure increases occurred. This fact allowed the model to be completed without modules representing the blowdown suppression tank and associated piping. REL, like PSY, is modeled as an automatically controlled and quick opening valve.

Finally, XC is also an automatic quick opening valve. It is the only part of the Emergency Core Coolant System used in the model. Since the high pressure injection flow is provided by a positive displacement pump, the actual upstream pressure of this valve always follows the downstream pressure. This effect was included by making the

pressure upstream a constant 20 psid greater than the cold leg pressure.

4.3.2.4 Connections

Three other modules, a flow divider called RXI, a junction called JUN, and a simple connection called PRX, complete the primary loop. RXI, located at the inlet of the reactor, divides the inlet flow into six streams: four are the reactor cold legs described in Section 4.3.1.1, one is the pressurizer spray line, and the sixth connects to the break connection valve, BRK, described earlier.

The junction module, JUNC, is required for the high pressure injection system connection. At the LOFT facility this connection, along with that of the pipe to the blowdown suppression tank, is at the coolant pump discharge. In the MMS model, two connections are needed because the injection flow is into the primary coolant system, while the flow to the blowdown suppression tank is out of the system. The MMS does not allow flow into and out of a system boundary at the same point.

The connection module, PRX, is needed because the pump, RCP, is a storage-resistive module, and would otherwise discharge directly into the reactor, a resistive-storage module, leaving two adjacent resistive nodes. (The dividing node is neither storage nor resistive). The MMS incompressible fluid connection module, appropriately

invoked by the command CONNI, is a storage module with a volume of zero.

The 14 modules of Section 4.3 which make up the primary coolant system, their joint configuration, MMS module names and LOFT facility model names are shown in Figure 14. The steam generator module of this figure is UTSGR. Figure 15 shows the substitutions made to use UTSG.

4.3.3 Secondary Coolant System

The secondary coolant system is modeled by up to five modules, in addition to the secondary side of the steam generator. These modules include three valves, one flow divider, and a connector.

4.3.3.1 Steam Control Model

The LOFT facility steam flow rate was varied by manual and automatic control in the transients examined in this study. The MMS, however, has no provisions for both types of control on the same valve. Therefore, two main steam control valves were used in the model, although the LOFT facility has only one. Under normal and anticipated transient conditions, both were not expected to be open at the same time, so that an abnormally high steam flow rate would not exist. Identical valve modules that allow for compressible flow, VALVEC, are used. The manually operated

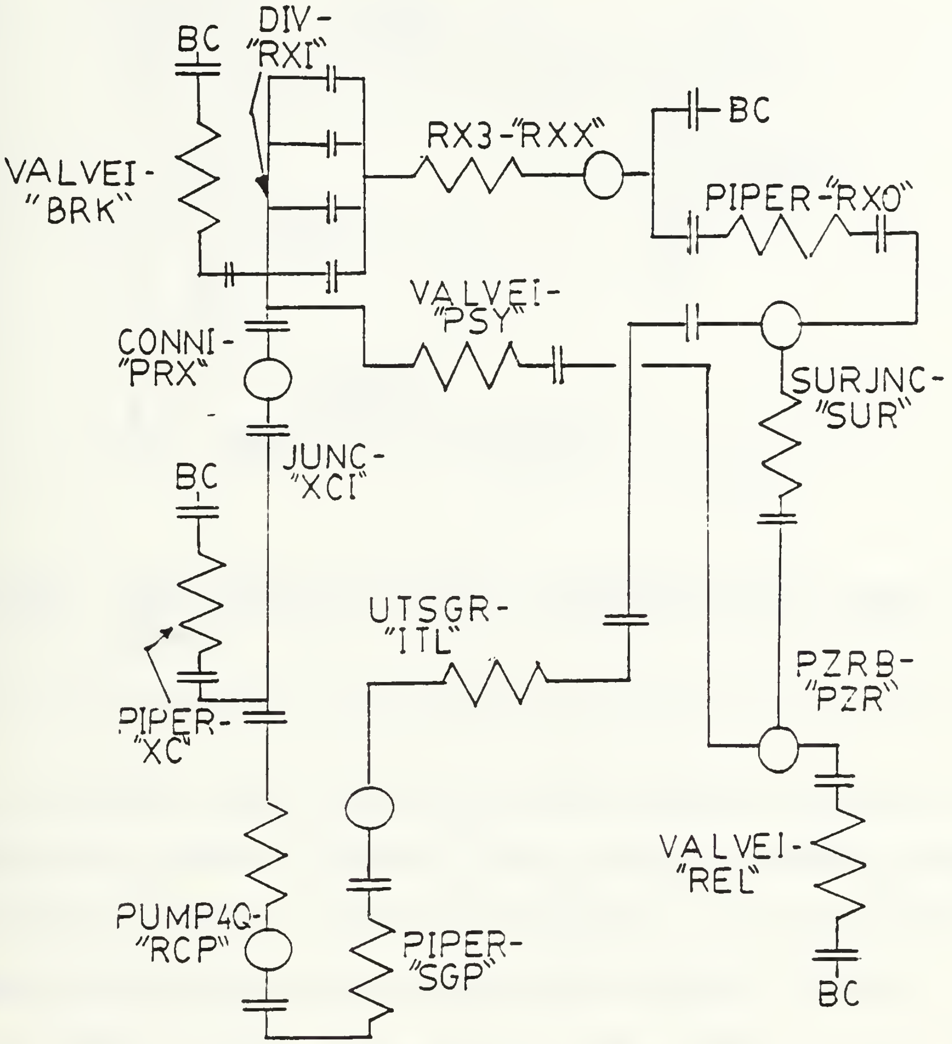

Figure 14: LOFT Facility Model (UTSGR Form)

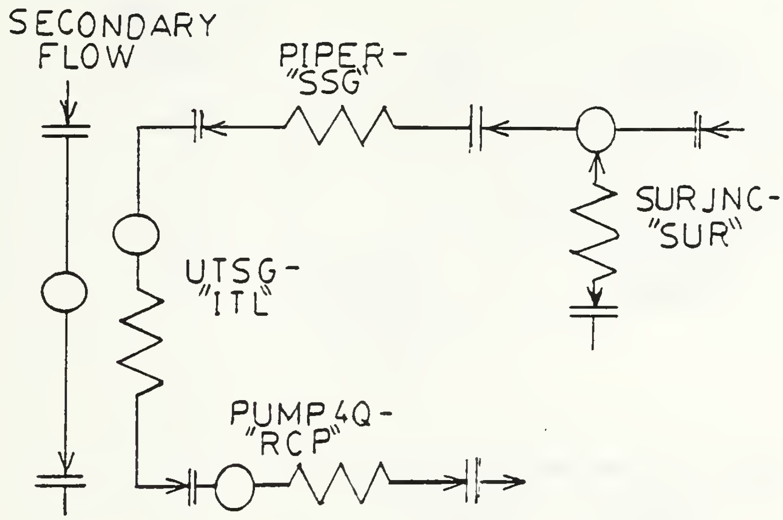

Figure 15: LOFT Facility Model (Substitutions made for UTSG)

valve is called MSS for main steam stop, and the automatically operated valve is MSR for main steam relief. At the LOFT facility, the relief function is accomplished by automatic operation of the normal flow control valve.

Flow from the steam generator to the steam valves is through the divider MSL to allow flow directly to whichever of the valves is open.

4.3.3.2 Feed System Model

The feed system consists of only two modules, the feed control valve FRV, and an incompressible connection RFW. Feed flow rate is normally controlled by the position of the

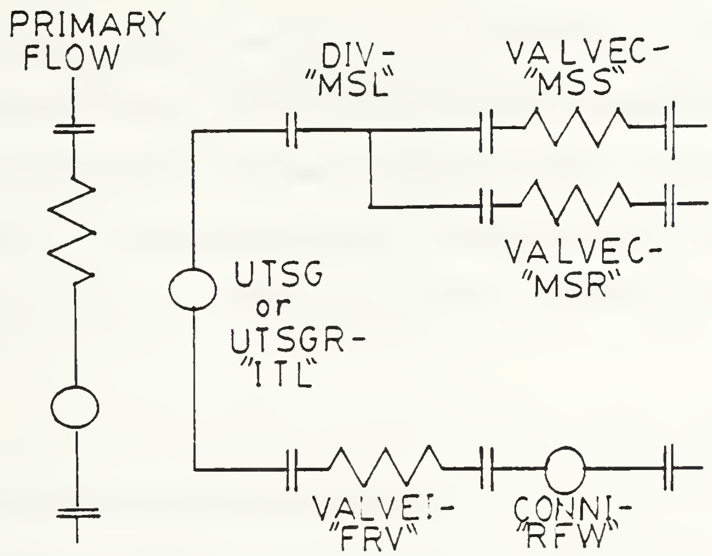

Figure 16: Secondary Coolant System Model

feed control valve. However, to accurately recreate the feed flow rate at the LOFT facility, RFW was added. To determine the effects of valve position on flow rate would have required an extensive testing procedure. Instead, use of a connective module allows flow rates to be input as a boundary condition.

The secondary coolant system model and module names are shown in Figure 16. Appendix B is a listing of all the non-control module names and their equivalent LOFT facility components.

4.3.4 Control Components

The only controllers needed in the LOFT facility model are on-off switches and their associated actuators. All automatically controlled valves require both a switch and an actuator module. The pressurizer heaters and the low pressure sensing reactor shutdown switch require only an on-off module.

4.3.4.1 Pressurizer Heater Control

The LOFT facility pressurizer has two sets of immersion type electrical heaters for automatic pressure control, the 12 kw cycling heaters and the 36 kw backup heaters. Each cycles on and off controlled by the pressurizer pressure. In the model this pressure is the variable PPZR. The MMS pressurizer modules allow for direct control of the heaters based on any system pressure selected by the modeler.

4.3.4.2 Rod Position Control

The low pressure automatic reactor shutdown or scram switch operates similar to the heater controllers, but with rod position as their output. This is the only automatic shutdown used in the model because it is the only one which occurred at the LOFT facility during the selected transients.

4.3.4.3 Valve Control

Table 4 lists the valves in the LOFT facility model which operate automatically, the parameter which controls them, and their associated actuator. These valves are part of both the primary and secondary systems, and perform a variety of functions. The other model valves are controlled by boundary value tables.

The total number of modules used in the LOFT model is 30: 14 in the primary coolant system, five in the secondary coolant system, and 11 control modules. Appendix C is the fully assembled LOFT facility model in MMS format.

4.4 Assembly Process and Initialization

Once the modules were selected and the initial parameters set, each was "operated" individually using as input the initial conditions of one of the transients described in Chapter 5. When a module operated satisfactorily in the correct steady state by itself, it was set aside and the next module was tested.

Assembly of the complete model began with the reactor, RXX, operating alone at 100% power, flow rate, enthalpies, and pressures. Next the hot leg pipe module, RXO, was attached. The now two-module model was operated until it worked satisfactorily in the steady state, and then another module was attached. This process of attaching a module and

Table 4: Model Valve Controllers

Valve	On-off Module Name	Controlling Parameter	Associated Actuator
Spray valve PSY	SVC	PPZR	PSY
High Pressure Injection XC	XCC	PPZR	XC
Pressurizer Relief REL	RVC	PPZR	REL
Main Steam Relief REL	MSC	Steam Dome Pressure PSTO	MSR

then testing to ensure the proper steady state parameters were calculated was repeated until the primary loop, without the connection from pump discharge to the pressurizer, was completed. The last module attached to complete the loop was the steam generator. Testing with this module in the system required that some of the constants, in particular the temperatures of the U-tube metal, be altered slightly from their calculated values. Since the calculated values of these temperatures were educated guesses at best, changing them slightly was not treated as a significant problem. When completed, the loop's heat balance, flow rates, and pressures were correct.

Next the spray valve connection was made to the reactor inlet piping. With this connection in place, the model would not operate at all. After a lengthy investigation into the problem, it was discovered that if a small flow resistance due to shear stresses was input into a relatively small diameter pipe, the model would stop execution. In this case, the resistance of the spray line was much less than that of the much larger sized reactor coolant inlet piping. The stop occurred because all flow would attempt to go through the much smaller spray line, causing flow reversals in the large dimension reactor inlet pipes. The MMS terminates execution if it senses such flow reversals. This problem was solved by decreasing the flow conductance (and thereby increasing the resistance) term of all the

small diameter pipes and valves in the model. RXO and SGP, the pipe modules representing the much larger hot and cold legs, respectfully, did not require large changes in their flow conductances. Only minor adjustments brought their differential pressures to the required values.

With the primary coolant carrying modules now all attached, the next step was to add the control modules. This step, also, was accomplished by adding one module at a time, followed by testing to ensure the entire model still operated satisfactorily. Addition of the pressurizer heater and spray controllers caused a somewhat awkward problem in that both the transients examined began with pressurizer pressure at about 2158 psia. The LOFT facility controllers, and those in the MMS model, are set to control pressure at 2250 psia. As Figure 17 shows, allowing the model to reach steady state causes some short fluctuations followed by a steady rise to the design pressure. Figure 18 shows the action of the heaters during the period that the model searches for its steady state. Note that all heaters are on until 350 seconds, when the backup heaters are de-energized. At steady state, the model runs continuously with pressure just below the turn-off set point of the cycling heaters.

Finally, the secondary modules were attached, using the same add and test process. The only significant adjustment required to the previously calculated secondary parameters was to the flow conductance of the main steam control valve,

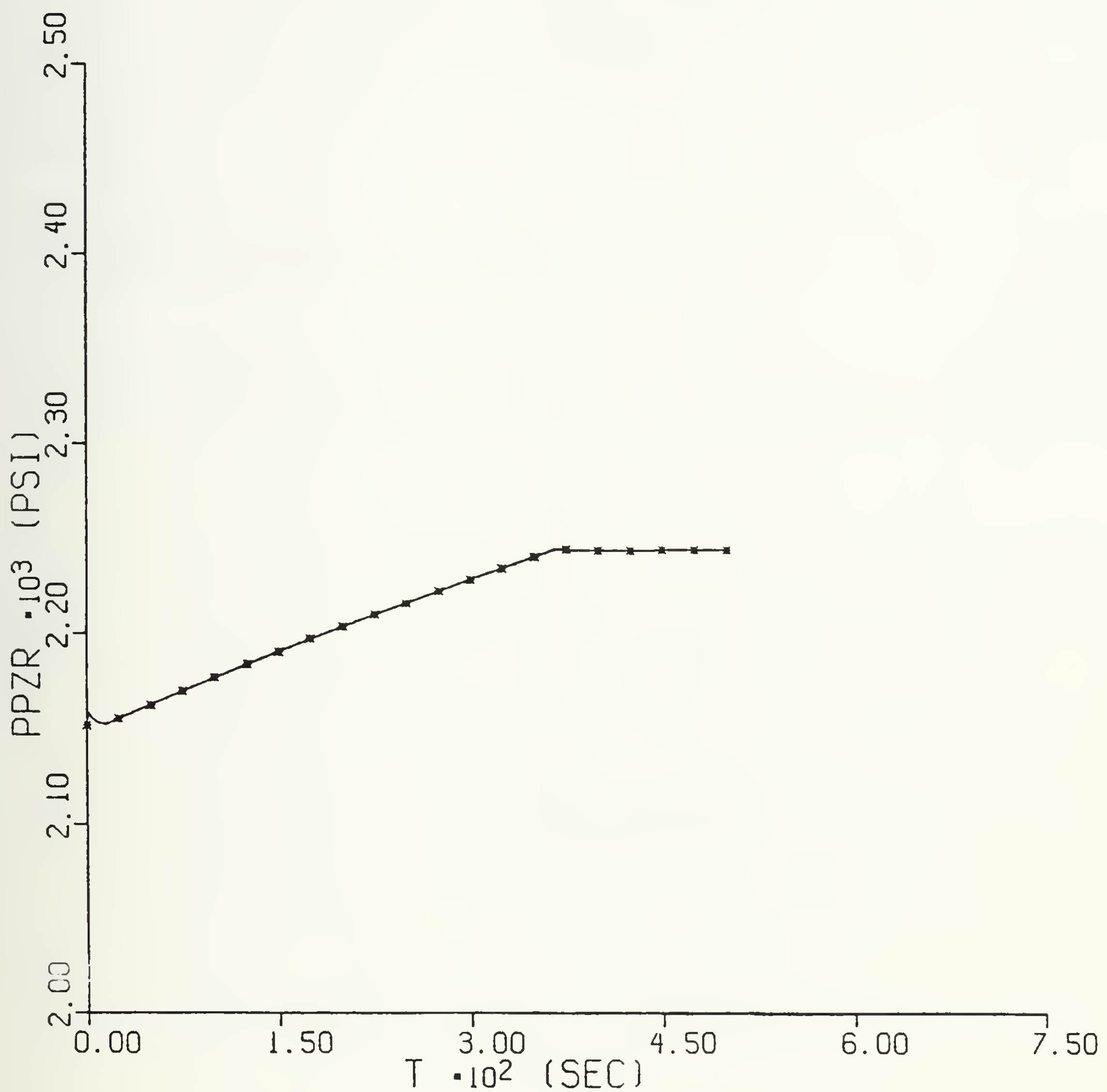

Figure 17: Pressure Trend During Initialization

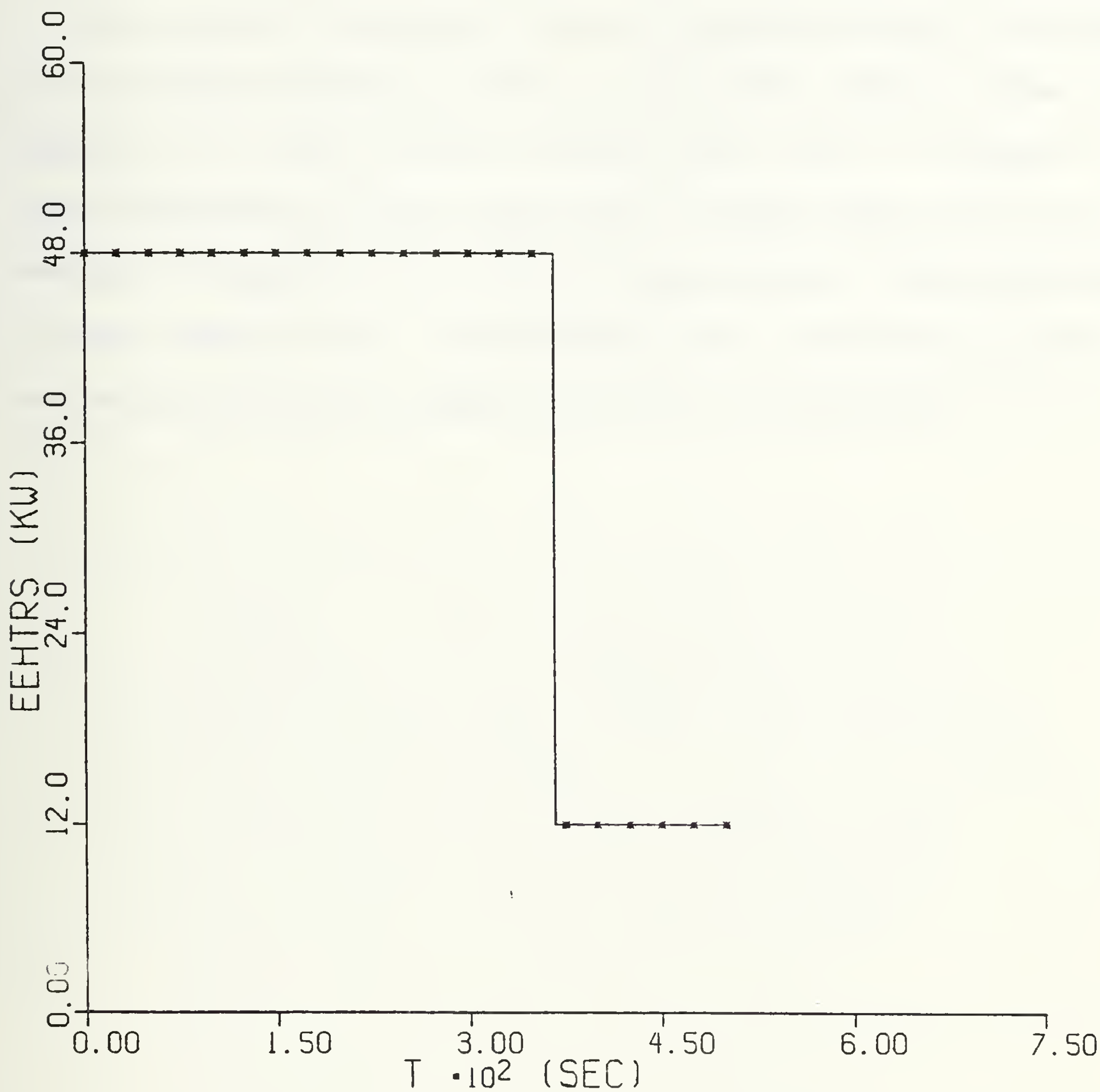

Figure 18: Heater Action During Initialization

MSS. This adjustment was needed to ensure that the steam flow rate out of the generator was maintained at 808 psia.

The constant parameters which required changes are shown as the first series of lines in the ACSL command files of Appendix D. This listing illustrates that to change an input parameter's value that has already been set by a FORTRAN statement, all that is required is a SET statement in the command file. Modification of the ACSL program, retranslation, and recompilation are not required.

Chapter 5

TRANSIENT DESCRIPTIONS

5.1 Selection Criteria

In order to validate operation of the MMS model of the LOFT facility under a variety of conditions, two transients were selected for analysis. The basic requirements to be met for inclusion of a transient in this study are listed in Table 5.

Table 5: Transient Selection Criteria

1) Adequate data had to be available for the key thermodynamic properties of both the primary and secondary coolant systems to at least 200 seconds after transient initiation;
2) The transients should include primary system pressure or power changes that initiate high pressure injection and/or a reactor scram;
3) Comparison data to another thermal-hydraulic reactor analysis code should be available.

Several of the LOFT facility experiments meet two or more of these criteria, so the selection was further refined to those transients which were initiated from easily achievable steady states. These steady states are those with the reactor at a constant power in the power range. Transient initiation from below the power range would have required either a steady state achieved from a previous scram

transient or elimination of the RX3 module, and use of an appropriate substitute as a source of decay heat. A steady state achieved from a previous scram transient was not acceptable because the ability of the MMS to model a LOFT facility scram had not been validated. As described in Chapter 1, this validation is the objective of this study.

Two experiments were chosen for analysis: L3-5, a small break loss of coolant experiment, and L6-3, a rapid rise in secondary coolant capability.

5.2 Transient Procedures and Significant Events

5.2.1 Small Break Loss of Coolant Experiment, L3-5

L3-5 is one of a series of six small break experiments performed at the LOFT facility soon after the Three Mile Island accident of 29 March 1979. The objectives of this series include:

> To determine the important plant thermal, hydraulic, operational, and neutronic phenomena during a variety of small break LOCEs (Loss of Coolant Events). . . .
> To evaluate the effectiveness of ECCS's in mitigating a slow depressurization transient. . . .
> To determine the effect of primary coolant pump operation on plant response.[7]

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[7] Leanne Thuy Lien Dao and Janice M. Carpenter, Experiment Data Report For LOFT Nuclear Small Break Experiment L3-5/L3-5A (Idaho Falls, Idaho: EG&G Idaho, Inc. 1980), p.3.

The objectives of the L3-5 phase were:

1. To conduct a small break depressurization in the LOFT facility with a 16.19-mm (0.6374-in.) diameter break orifice in the intact loop cold leg between the primary coolant pump and the reactor vessel, with primary coolant pump trip at the rupture, with the HPIS injecting into the reactor vessel downcomer, and with the accumulator isolated from the intact loop

2. To measure the primary system coolant inventory and system coolant mass distribution as a function of time during the depressurization using available instrumentation.[8]

5.2.1.1 Initial Conditions

The initial operating conditions at the facility for experiment L3-5 are presented in Table 6. These data are the actual measured values of the parameters listed, which are not necessarily those values intended by the operators. However, all the initial conditions presented are within 2 of their specified values, except for pressurizer liquid level and steam generator water level. These were 0.12 m above and 0.06 m below their specified values, respectfully. Listed with the actual values in Table 6 are those calculated by the MMS model after it achieved steady state. There are significant differences between the actual and MMS values of steam generator level and boron concentration. The boron concentration difference was ignored because the reactor was shutdown by a scram 4.8 seconds before transient initiation, and only decaying fission products affected the

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[8] Dao and Carpenter, pp. 3-4.

Table 6: Initial Conditions for L3-5

Parameter	Initial Values LOFT	MMS
Primary mass flow rate (lbm/hr)	3.77×10^6	3.78×10^6
Hot leg temperature (°F)	577.4	577.8
Cold leg temperature (°F)	545	542.7
Pressurizer pressure (psia)	2158.2	2158
Pressurizer level (ft)	4.16	4.18
Boron concentration (ppm)	650	1350
Control rod height (% withdrawn)	83	81
Reactor power level (MW)	49	50.8
Secondary mass flow rate (lbm/hr)	209088	224730
Steam generator level (ft)	10.3	16.83
Steam generator pressure (psia)	809	808

heat generation within the reactor. However, the steam generator level problem may have had some effect on the MMS's ability to predict heat removal performance, since the higher downcomer level indicates a larger liquid mass on the secondary side.

Attempts to change the liquid level by changing the physical parameters used in the input calculations only succeeded in radically altering other steam generator parameters, including the rate of heat transfer out of the primary system. Since the heat balance on the steam generator with this water level was very nearly correct, it was decided to continue the transient calculations from this point.

Since the highest rates of change of the parameters of interest occurred within the first 200 seconds of this experiment, this is the only period examined in this study. However, reference [4] contains experimental data to 2400 seconds if needed for future investigations.

5.2.1.2 Significant Events

Preparations for experiment L3-5 began by taking the reactor critical about 45 hours prior to transient initiation, and raising the power level to 49.3+.7 MW at 35.9 hours prior to initiation. This power level was maintained to allow a near equilibrium buildup of decay heat generating fission products. Such an equilibrium would then

simulate a power station operating many days at near 100% rated power.

At seven minutes prior to initiation, the instrumentation and recording systems were turned on, and at T=-4.8 seconds, the reactor was manually scrammed. With the indication of four "rod bottomed" lights at T=-2.8 seconds, the experiment was begun. (All times are referenced to T=0, the point at which the leak was begun.)

At T=0 seconds, the small leak was simulated by opening a valve in the drain line between the reactor coolant pump discharge in the cold leg and the blowdown suppression tank. This is the valve modeled by BRK in the MMS model. The initial flow rate into the blowdown suppression tank was 43000 lbm/hr. This rate decreased rapidly to 25000 lbm/sec. at T=150 sec. At this point the flow rate out of the primary system slowly dropped until the experiment was concluded at 2309 sec. after initiation. The leak was sized to simulate a four-inch-diameter break at an actual 3000 MW(t) PWR plant. Sizing was accomplished by using an orifice in the drain line.

At T=0.8 seconds, the reactor coolant pumps were tripped. The pumps coasted down until their motor breakers tripped open at T=17.7 seconds. This marked the end of the coast down and the end of forced circulation of the primary coolant. Interestingly, natural circulation was detected as soon as T=17 seconds, indicating that flow never fully stopped.

At T=4.0 sec., HPIS flow was initiated into the reactor downcomer, and continued until past the time of interest in this study. In the MMS model of the LOFT facility, this flow is into the reactor coolant pump discharge. Since the ultimate effect of the HPIS flow is to mitigate pressure losses and to maintain coolant inventory, the location of injection should not have made a difference in the MMS predictions. Automatic initiation of injection began when the primary system pressure reached 1915 psia. None of the references used in this study indicated precisely where this pressure was measured, so it was assumed to be in the intact loop hot leg. In the first four seconds of this experiment, pressure dropped 243 psia to reach the HPIS injection set point. Such a rapid change was caused by both the coolant shrinkage due to the scram and the loss of coolant through the simulated leak. A large amount of heat was still being drawn off by the steam generator because the main steam isolation valve requires about 10 seconds to shut. This valve began to close shortly after the scram, but was not fully closed until T=5.2 seconds.

At T=22.2 seconds, the pressurizer was emptied. Pressure in the pressurizer at this point was 1450 psia. About 6.2 seconds later, the reactor's upper plenum reached saturation conditions of 572°F and 1250 psia. Here the pressure drop slowed considerably. At T=30.0 seconds, hot leg voiding began, and at T=80.0 seconds, cold leg voiding began.

Finally, at T=92.9 seconds, flow through the leak reached saturation. At T=200 seconds the primary system pressure was down to 986 psia.

The only other significant event to occur in the first 200 seconds of L3-5 was the automatic initiation of auxiliary feed flow at T=63 seconds. This flow continued until well past the 200 second mark. In the MMS model, this flow is provided by a table of boundary values.

Figures 19, 20, and 21 show the changes of some significant parameters of this experiment, along with the changes predicted by the RELAP code, if available.

5.2.2 Excessive Steam Load Experiment, L6-3

The objectives of the L6 series of experiments include:

> - determine the important thermal, hydraulic, operational, and neutronic phenomena during an anticipated transient at the LOFT facility and to identify any unexpected behavior . . .
> - provide data to evaluate reactor transient analysis techniques used to analyze anticipated transients . . .
> - provide data to assist in analyzing the relationship between behavior in LOFT and in a commercial PWR during anticipated transients.[9]

The specific objectives of the excessive steam load experiment, L6-3, were:

> a. Investigate plant response to a transient in which the heat removal capability of the secondary system is significantly increased
> b. Provide continued evaluation of automatic recovery methods

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[9] Nalezny, p. 9-1.

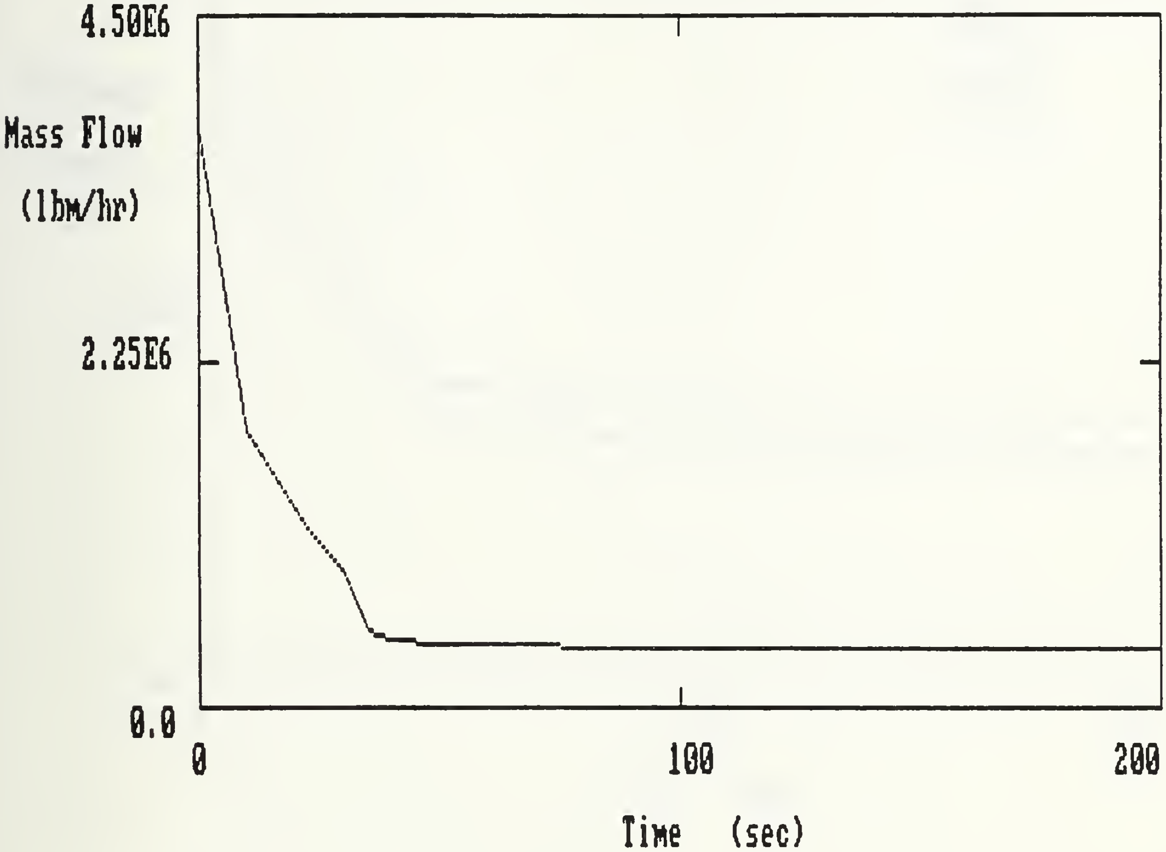

Figure 19: Experiment L3-5: Hot Leg Flow Rate

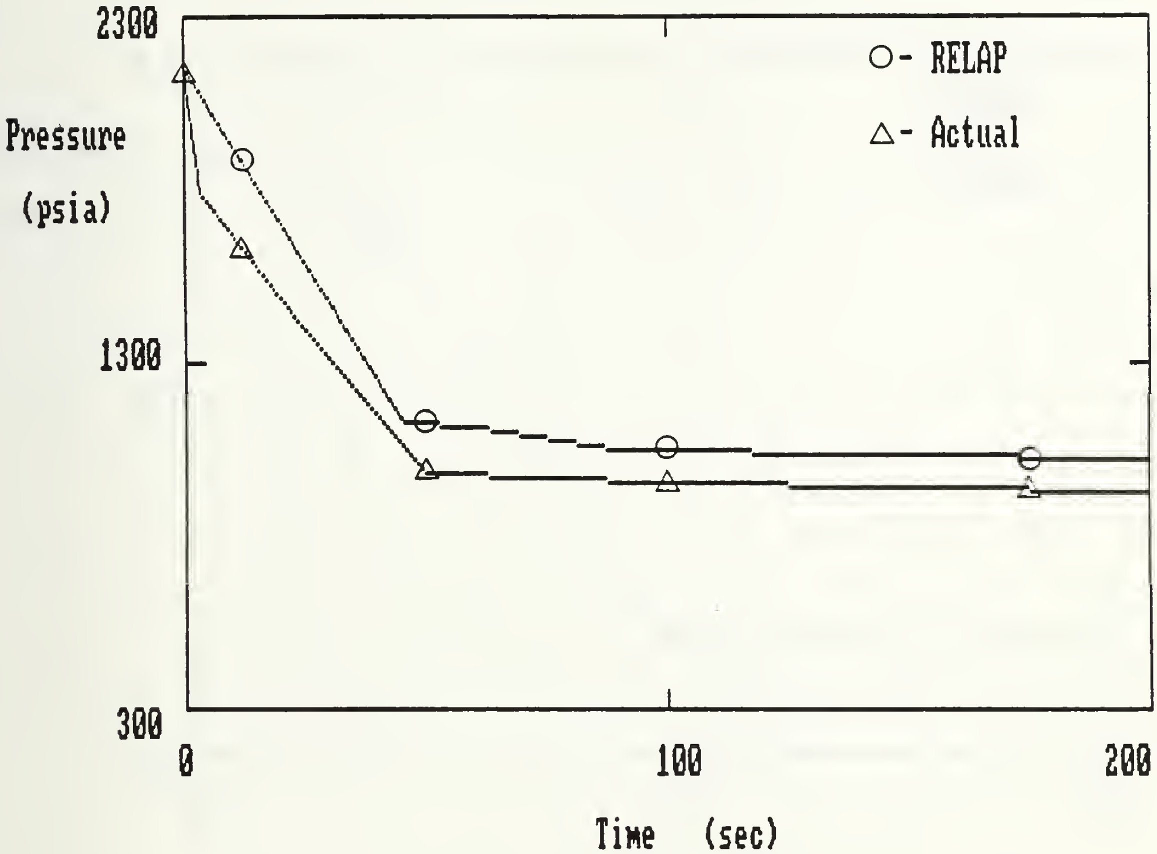

Figure 20: Experiment L3-5: Primary Coolant System Pressure

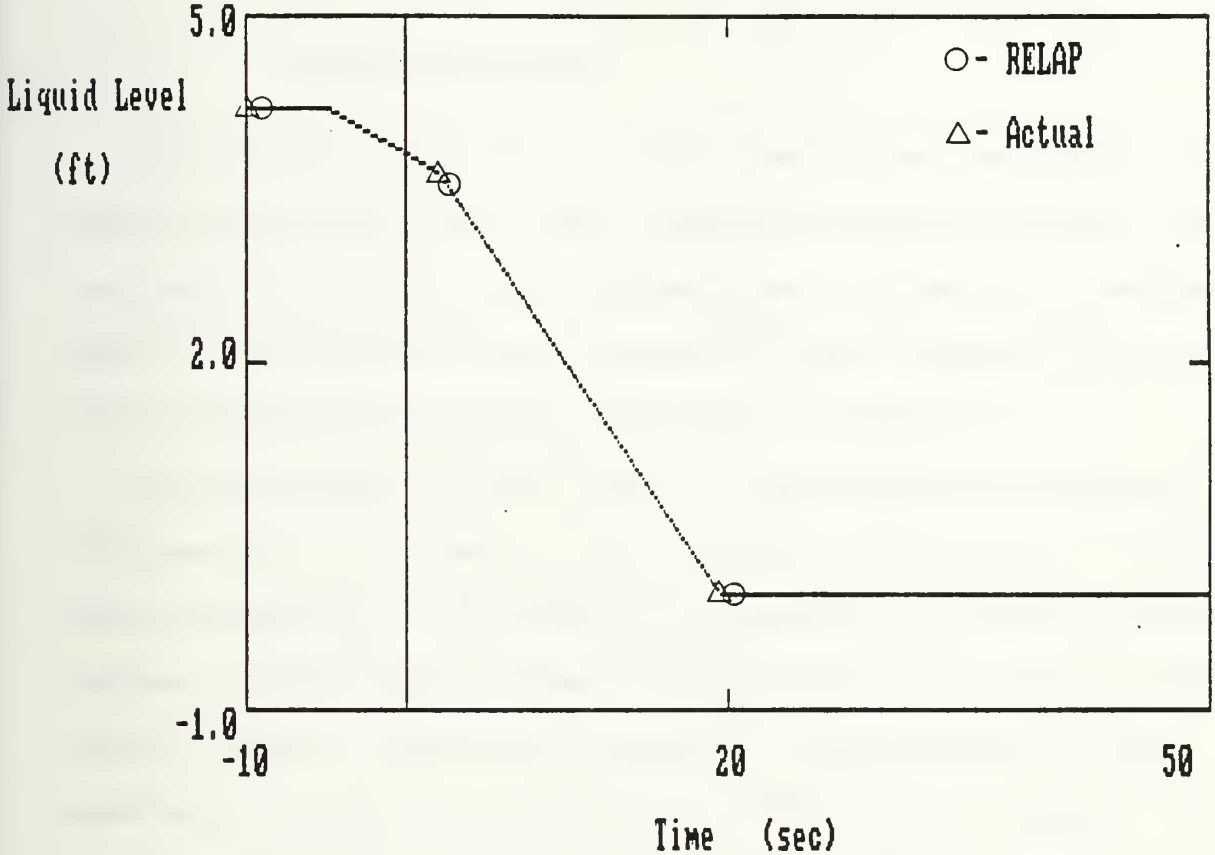

Figure 21: Experiment L3-5: Pressurizer Level

c. Provide data to evaluate code capabilities for secondary system initiated events.[10]

5.2.2.1 Initial Conditions

The initial conditions for this experiment were much the same as those of L3-5, with the major exception being that the reactor was at 75% of rated power instead of at maximum power. The actual initial conditions are listed with those of the MMS model for this experiment in Table 7.

Of significance is the lower steam generator pressure, 775 psia at 75% power vs. 809 psia at 100% power. This lower pressure was difficult to recreate in the MMS model because reducing the steam flow by closing the main steam control valve caused an increase in the model's steam generator secondary side pressure. This is, of course, what would happen in an actual reactor plant without some sort of automatic primary temperature control. However, the average primary temperature in the U-tubes was 548.5°F at 75% power, compared to 560°F at 100% power. This indicated that the facility's reactor has a load following primary temperature control system, although such a system was not described in any available reference. Modeling this system was not required to meet the objective of this study, but the changes from the L3-5 initial conditions to the L6-3 initial conditions were required. Hence, an entirely new

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[10] Nalezny, p. 9-2.

Table 7: Initial Conditions for L6-3

Parameter	Initial Condition LOFT	MMS
Primary mass flow rate (lbm/hr)	3.80×10^6	3.85×10^6
Pressurizer pressure (psia)	2193.7	2194.7
Cold leg temperature (°F)	535.3	538.2
Hot leg temperature (°F)	561.7	564.8
Reactor power level (MW)	36.9	38.0
Control rod position (% withdrawn)	81	81
Pressurizer level (ft)	3.94	3.90
Secondary mass flow rate (lbm/hr)	163944	163940
Steam generator pressure (psia)	775	773.6

set of steady state parameters was developed. The model's primary temperature was lowered by raising the boron concentration to 1397 ppm, or 52 ppm more than the level for L3-5.

5.2.2.2 Significant Events

Criticality for experiment L6-3 was achieved about 16 hours prior to experiment initiation. At about 4.5 hours prior to initiation, power was raised to 49.5 MW, and then lowered to 36.9 MW (75% rated power) just before the experiment was begun.

L6-3 was initiated at T=0 seconds by ramping open the steam flow control valve from the 75% power position. As steam flow increased the cold leg temperature dropped, causing an increase in the reactor power level due to the negative temperature coefficient of reactivity. Power reached a maximum of 42.2 MW at 15.6 seconds, when the reactor scrammed. Scram was initiated automatically upon receipt of a low primary system pressure signal at 2080 psia in the intact loop hot leg.

The pressure decrease continued because of delays in reducing the steam flow. The steam flow control valve was not completely shut until T=36.2 seconds. At the LOFT facility, this valve shuts automatically upon receipt of a reactor shutdown signal. Delays in reaching the fully shut position include time for a "close" signal to be sent to the

steam flow control valve actuator, time to reverse the direction of travel of the control valve, and the travel time to reach the fully shut position. These delays totaled about 20 seconds. The feed pump was tripped immediately after the scram.

The HPIS pumps started automatically at T=26.4 and T=26.6 seconds when primary system pressure reached 1915 psia. The pressure drop was immediately mitigated, and within ten seconds, pressure began to rise again. The HPIS pumps were shut off by the operators at T=48.6 and T=50.0 seconds, with pressure at 2100 psia. By the end of the period of interest, 200 seconds after experiment initiation, pressure had almost returned to the automatic control band.

Decay heat input to the primary coolant was near its maximum possible rate because of the previous operating history near 100 power. The reactor decay heat generation exceeded the steam generator heat removal at T=33 seconds. This effect, too, helped to quickly restore pressure to its normal level.

Figures 22, 23, and 24 show the changes in steam demand, reactor power, and primary system pressure, respectfully, that occurred during this experiment. Also in these figures are the applicable RETRAN predictions.

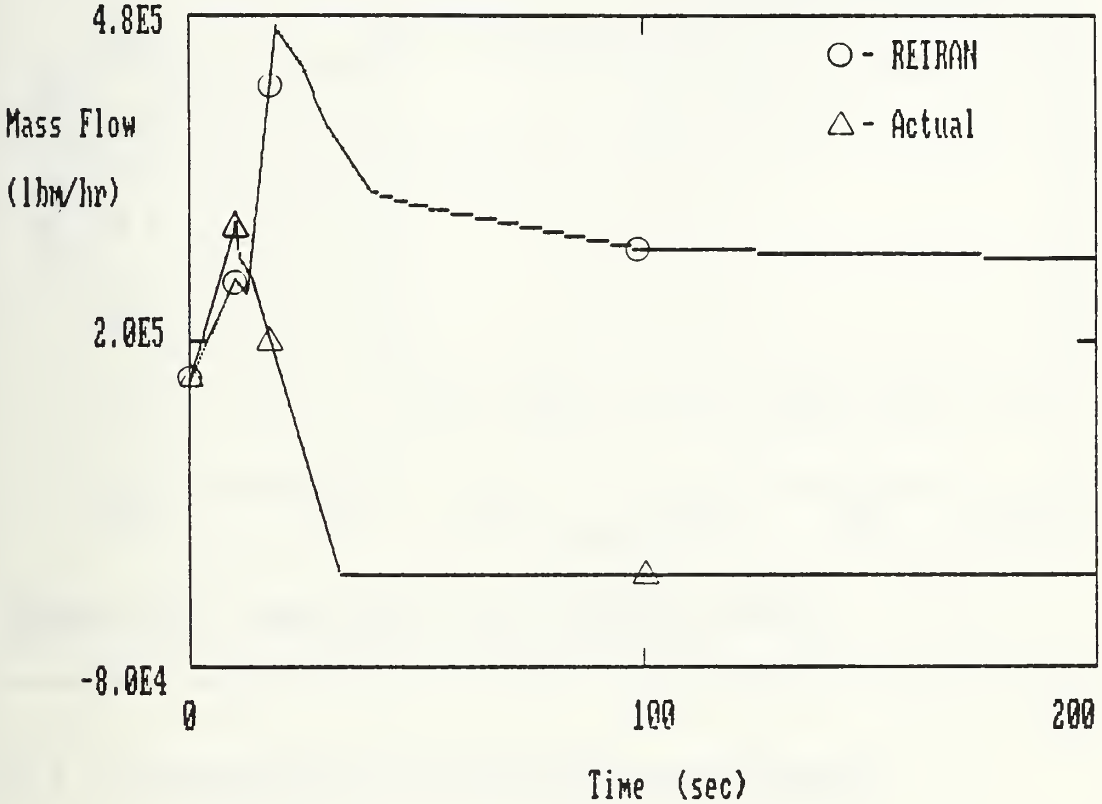


Figure 22: Experiment L6-3: Steam Demand

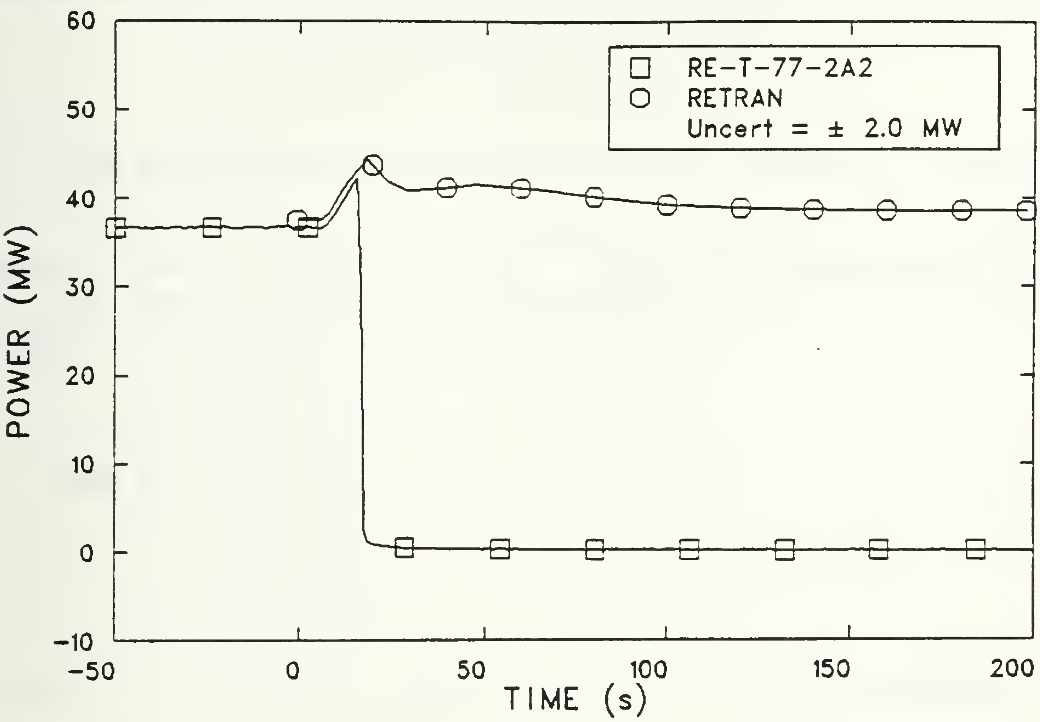


Figure 23: Experiment L6-3: Reactor Power

5.3 Applicability to the Validation Process

It should be noted that both of these transients involved large changes in primary pressure after a reactor scram. However, experiment L6-3 was not as "violent" as L3-5 because no loss of coolant occurred, the primary coolant pumps were not shut off, and saturation conditions did not occur in the hot leg piping. These two experiments, then, compliment each other in the MMS validation process. It was considered possible that the MMS could handle predicting the LOFT facility performance in L6-3, yet not be appropriate for such severe transients as those of L3-5.

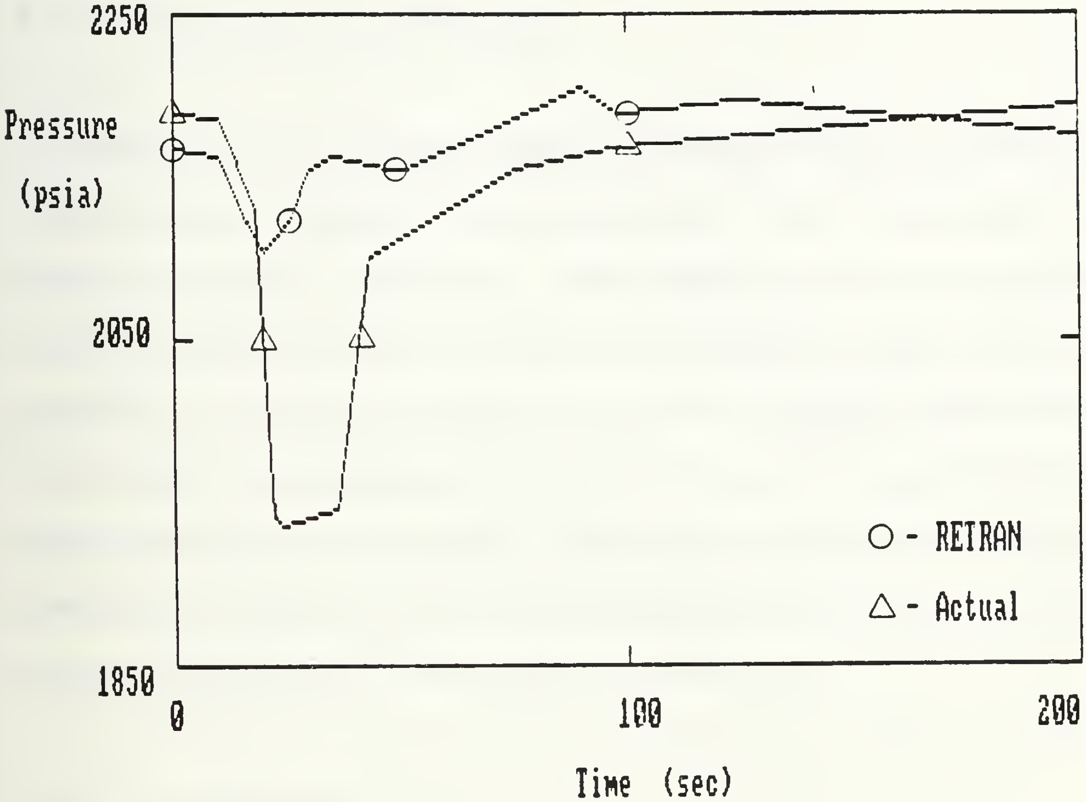


Figure 24: Experiment L6-3: Primary Coolant System Pressure

Chapter 6

PERFORMANCE OF THE MODULAR MODELING SYSTEM

6.1 Experiment Predictions

Operation of the MMS models produced output consisting of many modeler selected thermodynamic state variables and module internal variables. Many executions were required to trim the model input so that reasonable output could be obtained. The first sections of this chapter describe the best model performances in predicting the parameters of experiments L3-5 and L6-3. The last section is included to demonstrate some of the problems that can be encountered when working with a code such as the MMS.

6.1.1 Experiment L3-5

The MMS predictions of the LOFT facility's thermal-hydraulic performance in experiment L3-5 begins with the reactor plant at steady state. The steady state operating parameters are listed in Table 6. To execute this transient, tables of various operator actions were made part of the ACSL program. The variables changed by these tables are the steam flow control valve position, the feed flow rate, and the position of BRK, the leak simulation valve. The L3-5 time references in this chapter begin at 10 seconds before the opening of the "leak" valve, BRK. Hence the

scram occurs at T=5.2 seconds, and BRK opens at T=10.0 seconds.

The parameters considered key in evaluating the transient performance of the MMS model are the pressurizer level, the primary system pressure, the primary coolant flow rate, and the steam generator secondary side pressure. These were selected because they can be used both as direct performance indicators and have the synergism to be used for interpreting other parameters. These other parameters include temperatures and mass inventory. Figures 25 through 28 show the actual reactor plant's trends of the four selected parameters compared with the MMS predicted values. The actual values are indicated by the symbol "□," the predicted values by the "*."

As these figures readily indicate, the MMS did not operate past 30 seconds into the transient. Discounting the first ten seconds used to adjust the zero marker and allow for the scram, less than 20 seconds of the actual transient are shown. Of approximately 200 attempted reinitiations and executions of experiment L3-5, the longest "real" time that was reached was achieved on the runs shown in Figures 25 through 28. It should be noted that a typical MMS run uses about 1 CPU second for each second of real time up to about 20 seconds, and 1 CPU second for 10 real seconds thereafter.

As shown in Figure 25, the MMS appears to accurately predict the changes in the primary coolant cold leg flow

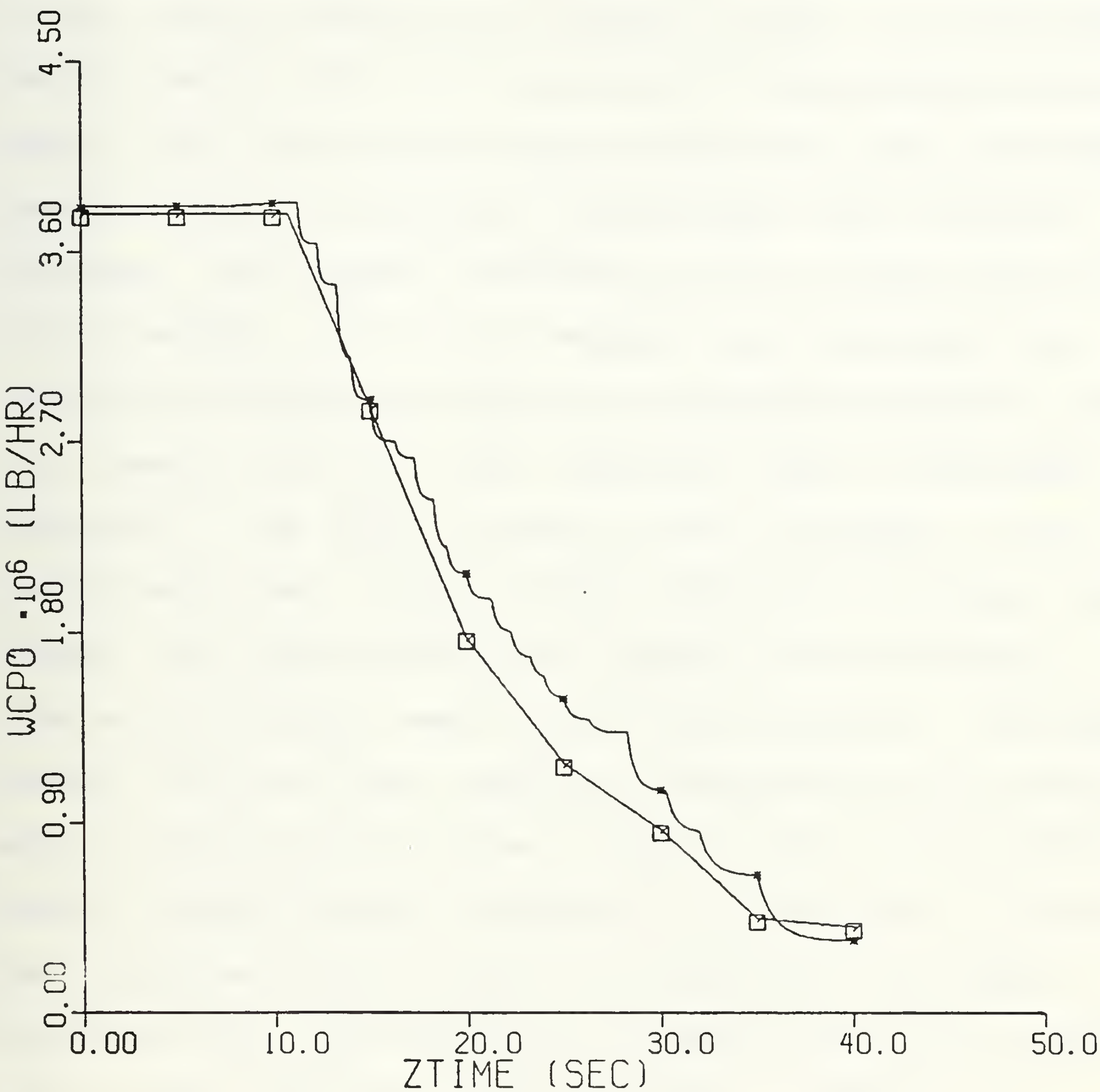


Figure 25: L3-5 Predicted Performance: Primary Coolant Flow Rate - Cold Leg

rate. By the built-in variable naming convention of the MMS, WCPO indicates this is a plot of the mass flow rate, W, at the location named by the modeler as CPO. In the LOFT facility model, CPO is the discharge of the primary coolant pumps. After the coolant pumps are shut off, pump coastdown takes a number of seconds, during which flow steadily decreases. The largest difference in flow rates occurs at T=28.0 seconds. Note that because the pump speed was entered as a series of steps using the ACTION command in the ACSL command file, the flow coastdown took a scalloped appearance. The ACTION command allows variables to be changed more than once in a single model run. However, the changes are instantaneous, as opposed to the smooth appearance of changes made using a TABLE command. The TABLE command, on other hand, requires recompilation of the entire model if even a single value is changed. Use of the ACTION command allowed frequent changes, at minimal cost, in the pump coastdown rate in order to extend the the model's operating time. The coastdown in Figure 25 is at the actual rate of the facility's coolant pumps. Changing the coastdown rate did not change the time at which model execution terminated.

Figures 26 and 27 show together the changing of the pressure in the primary system, with the accompanying lowering of the pressurizer water inventory.

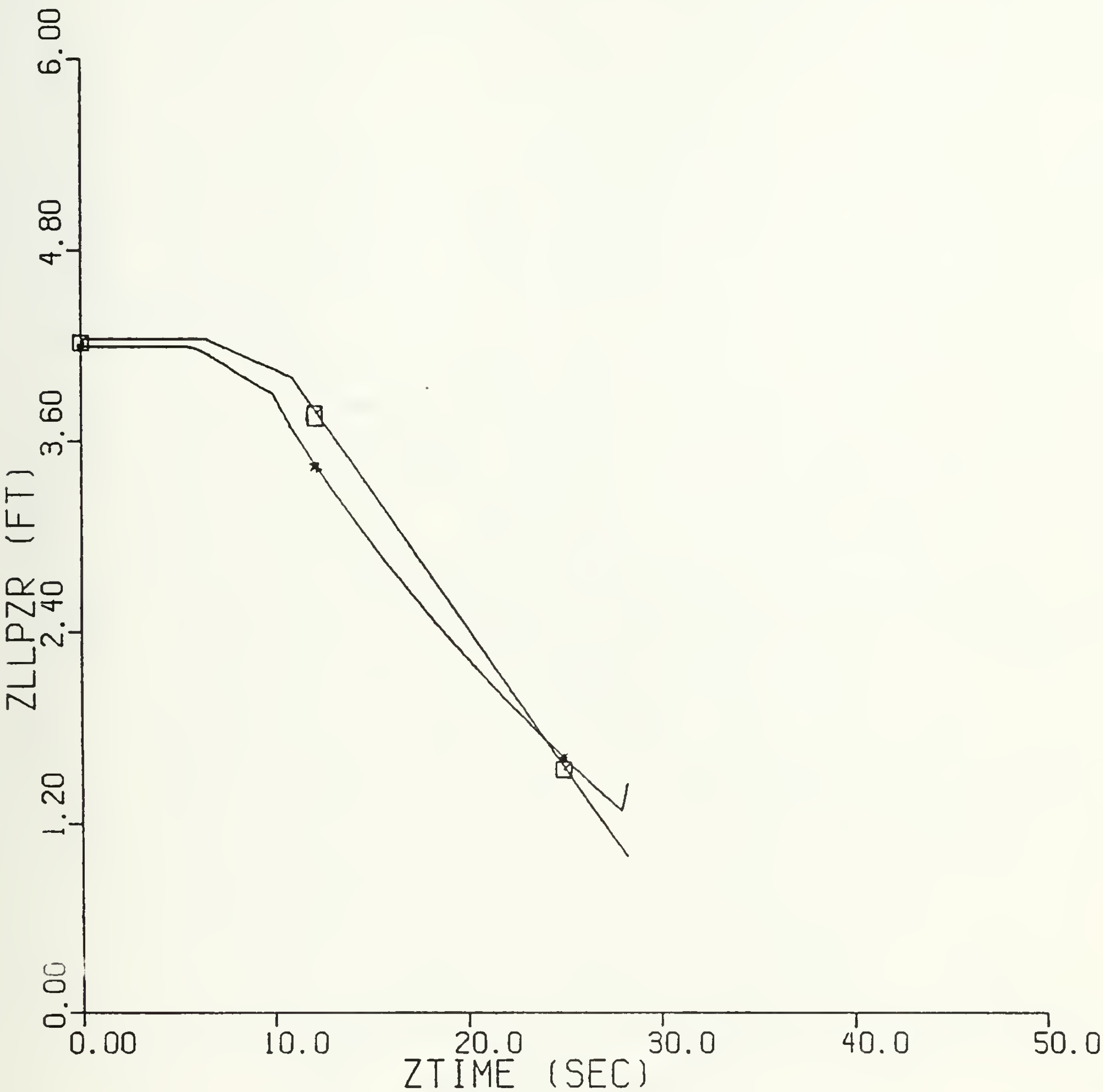


Figure 26: L3-5 Predicted Performance: Pressurizer Water Level

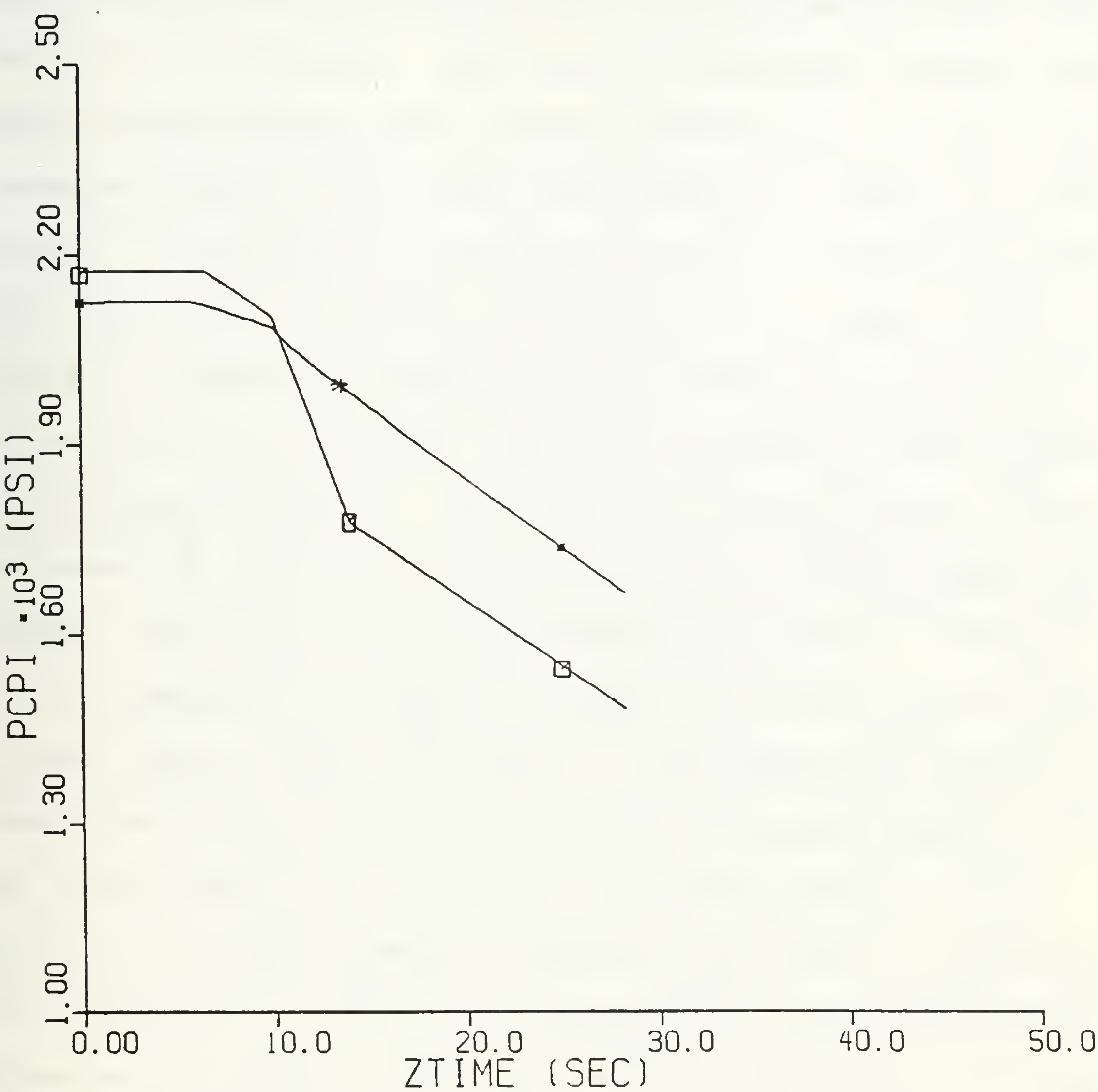


Figure 27: L3-5 Predicted Performance: Primary System Pressure

ZLLPZR and PPZR are the MMS names for pressurizer level and pressure, respectfully. The predicted level and pressure drop slowly after the scram, and at an increasing rate when the leak is initiated. The drop in the level follows the actual rate initially, but slowly decreases due to the high pressure injection flow until the levels are equal at T=25 seconds. High pressure injection was also initiated at the LOFT facility, of course, but its effects seemed to be masked by instrument inaccuracies. Execution termination occurs shortly thereafter, with an interesting sharp upturn in the predicted level. This upturn is the leading clue to the cause of the failure of the model to continue past 30 seconds. This failure will be discussed further in Chapter 7. The pressurizer pressure diverges from the actual value at the time of leak initiation. The predicted pressure change does not reach the high rate of change measured at the actual reactor. At T=12.5 seconds, shortly after initiation of high pressure injection, the rate of change of actual pressure slowed. Here the predicted and actual rates became nearly equal. The error between predicted and actual values at 28.5 seconds is 11.7%.

Finally, Figure 28 shows the pressure in the steam generator begins to increase after the flow control valve is shut, as expected. The model predicts a much faster initial rise in the pressure, but then appears to slowly approach steady state. Of course, what happens after 30 seconds is

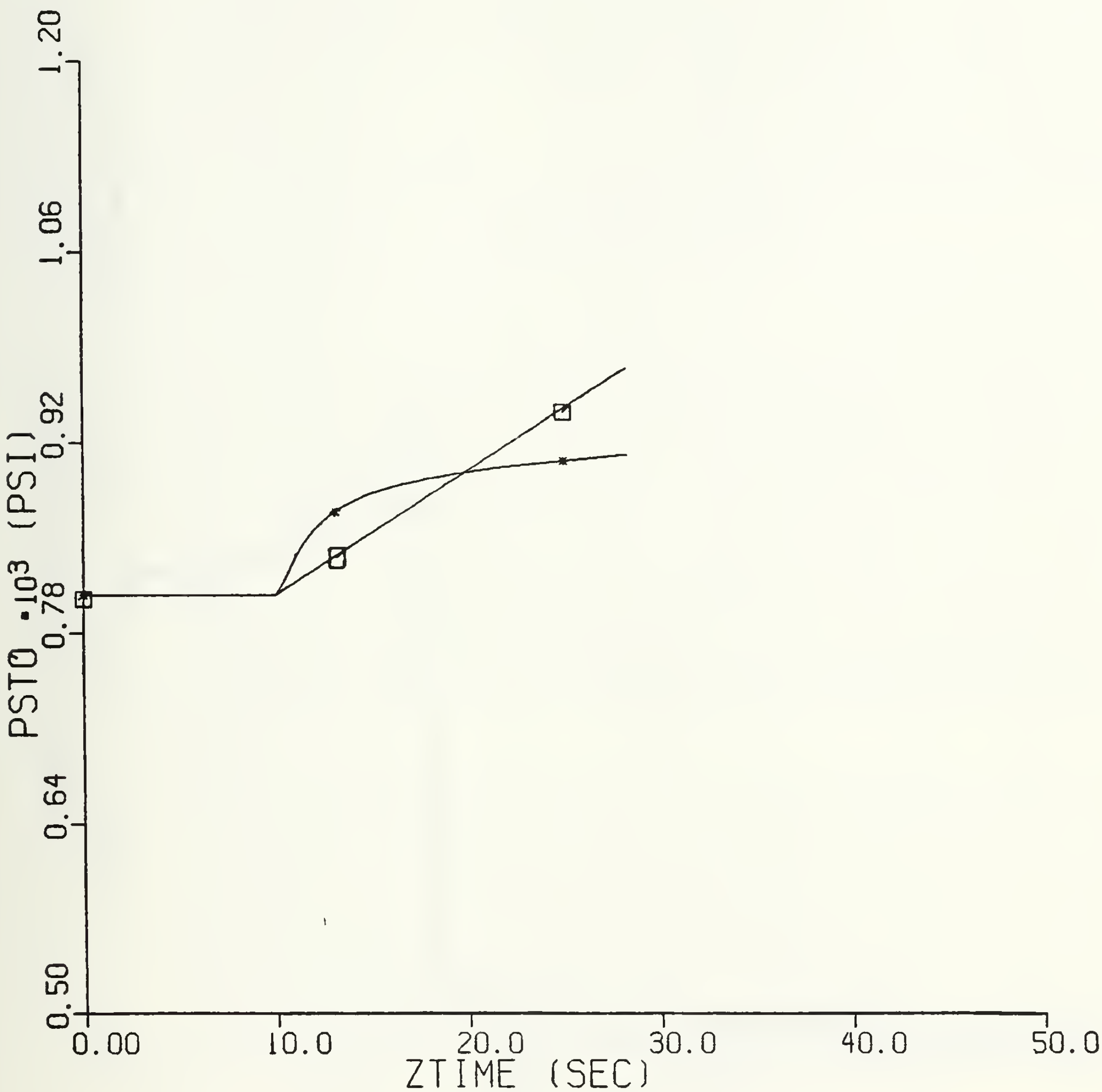
not known, but it appears that the predicted steam generator pressure would never reach the relief valve setpoint, while plant data shows that the actual relief valve did open.

6.1.2 Experiment L6-3

Figures 29 through 31 show the trends of the key parameters of experiment L6-3. For this less severe transient, the primary flow rate is not shown because the pumps were not shut off, nor is the steam generator secondary side pressure. Changes in this pressure were instead used as input data, along with the secondary flow rate, to initiate the transient on the model. Added to the figures is reactor power, shown in Figure 29.
Since this transient began with the opening of the steam flow control valve at a time of 0 seconds, the figures used for the evaluation also begin with a time of T=0 seconds.

Of immediate note is that the MMS operated to the intended end of the transient, 200 seconds. The power trend is plotted for only the first 50 seconds because once the reactor was shut down, the MMS predicted power remained consistently about 5% above the the actual plant data. The 50 second plot expands the first part of the transient for better clarity.

The key differences between the actual and predicted performance of the reactor power are the rate of change of power while steam flow was increasing and the maximum power



<u>Figure 28</u>: L3-5 Predicted Performance: Steam Generator Pressure

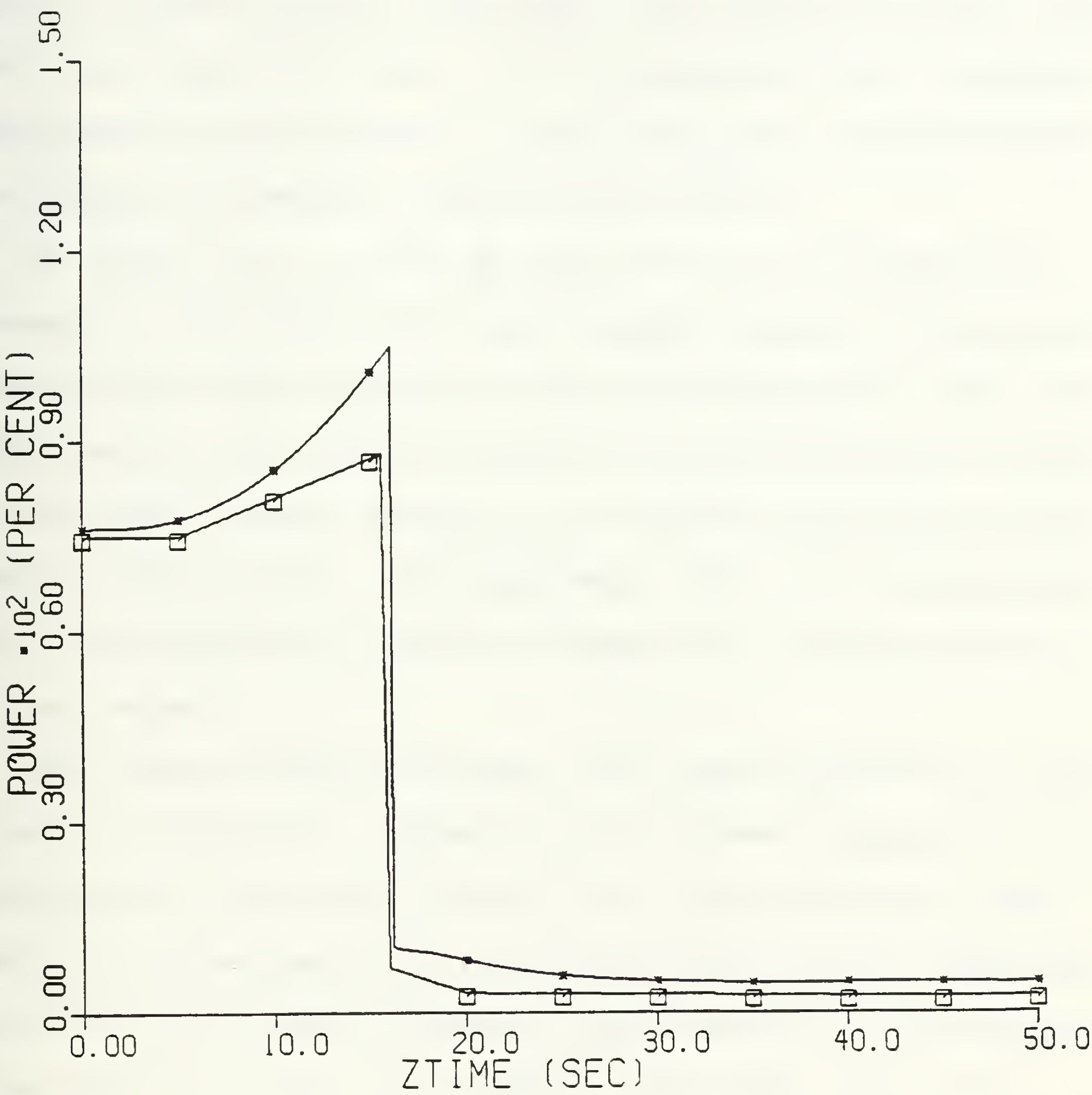


Figure 29: L6-3 Predicted Preformance: Reactor Power Level

reached before the reactor is automatically shut down. The MMS rate is higher and thus when the reactor scrams on low primary system pressure the model power peaks at 100% while the actual power was 86% . If the model had also included a high power scram setpoint, it may have been reached before the reactor scrammed on low system pressure.

In Figure 30, it can be seen that the pressurizer pressures initially track very closely together through the time of the scram and up to about T=20 seconds. Both the LOFT facility and MMS low pressure scram set points are set to initiate reactor shutdown if pressure drops past 2130 psia in the hot leg. In experiment L6-3, as in experiment L3-5, the predicted pressure drops more slowly than the actual value.

The pressure drop continues until the initiation of high pressure injection. Because of the slower pressure drop predicted by the MMS, HPI does not come on until T=36 seconds, 10 seconds after the actual initiation. The slow reversal in the rate of change from negative to positive is predicted to occur more rapidly than did the actual reversal. Hence the minimum pressure reached by the model is 1960 psia, while in reality, pressure reached a minimum of 1940 psia. Of note is the almost immediate mitigation of the rapid pressure change by the model.

With the HPI system running, the predicted pressure rises at nearly the rate of the actual increase. The actual HPI

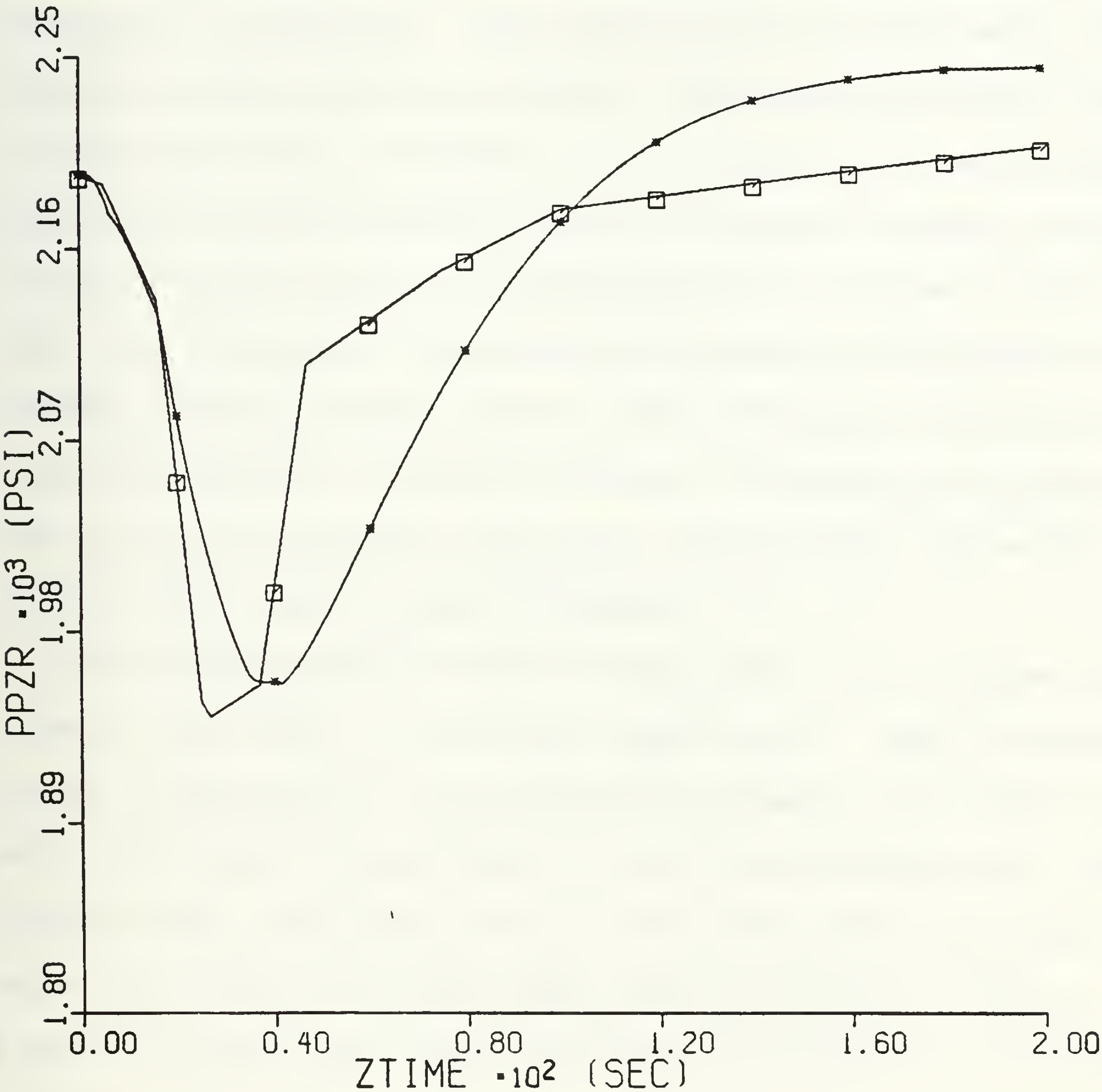


Figure 30: L6-3 Predicted Performance: Pressurizer Pressure

pumps were turned off by the operators, causing the sharp change in the rate of pressure increase when pressure had returned to 2100 psia. This pressure is 70 psia below the automatic pump shutoff set point. Using only an on-off type of controller for the HPIS, both automatic and manual pump operation was not allowed. Hence the model's pumps are not turned off until primary system pressure returns to 2170 psia. At this point the predicted pressure rise slowed, and primary system pressure control was eventually returned to normal operation. At T=200 seconds, the predicted pressure was back in the normal operating range, while the actual pressure had reached only 2105 psia.

The predicted water level of the pressurizer tracked very closely with that of the actual experiment. Again, because of the slower drop in the predicted pressure, the time at which the level is predicted to reach its minimum is a few seconds after the actual time. The final predicted level is above that of the actual level with an error of 7.8%. Figure 31 shows the actual and predicted values of the water level.

6.2 Unsatisfactory Model Execution

As described earlier in this chapter, many executions of the MMS models were required to arrive at the results of Figures 25 through 31. Figures 32 through 35 show the

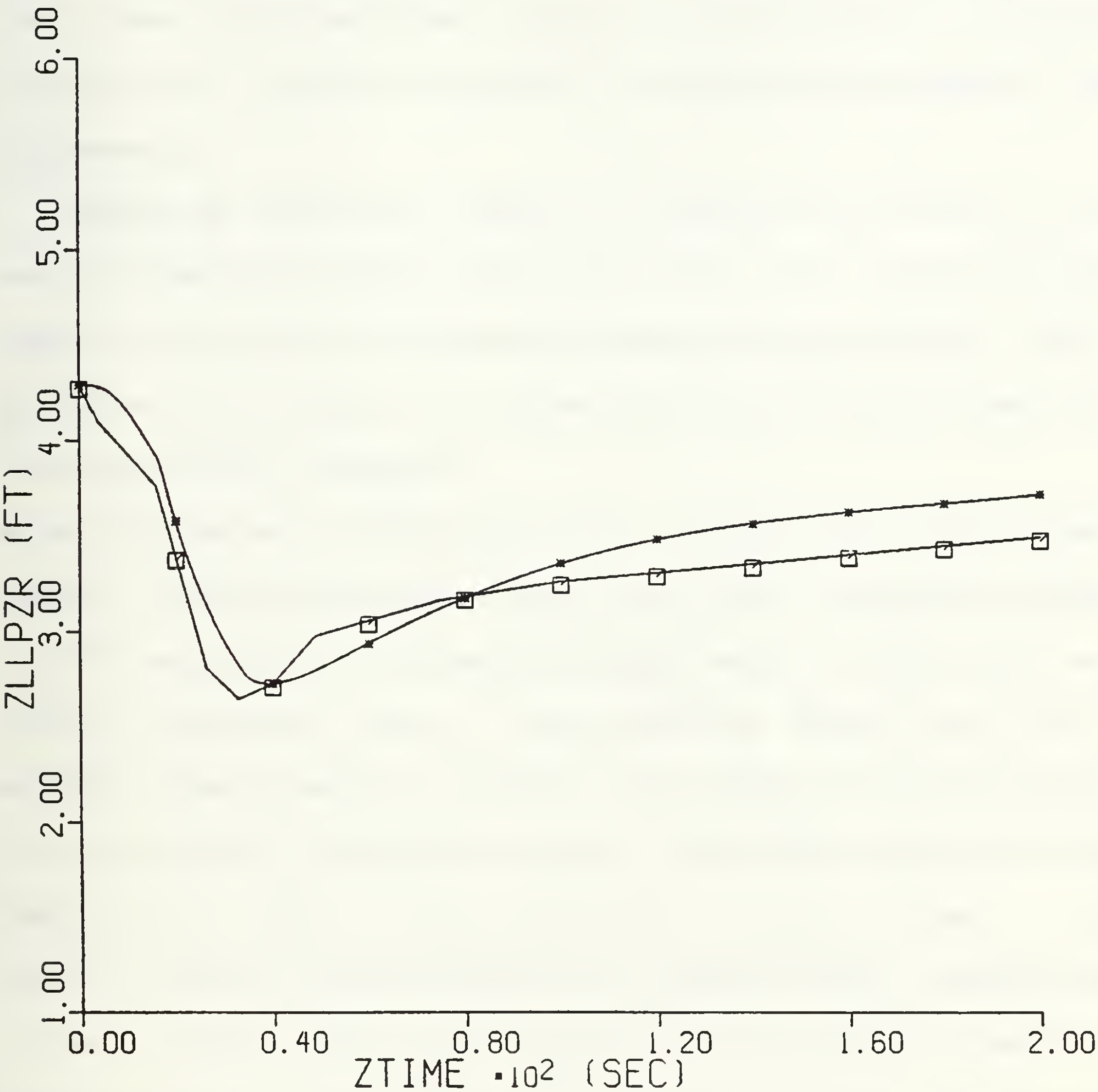


Figure 31: L6-3 Predicted Performance: Pressurizer Level

results of some unsatisfactory runs. Although these executions are termed unsatisfactory, they were not without use. Most provided some indication of a cause of execution failure or a required adjustment in one of the model's input parameters.

Figure 32 shows the change in pressurizer level on an early attempt at predicting experiment L3-5. The pressure shown is that at the primary coolant pump suction. This pressure is initially, as expected, about 20 psia less than the pressurizer pressure.

After the scram at T=5.2 seconds, the pressure drops a small amount, but then begins a slow climb past its initial value. At T=35 seconds, the pressure again began to drop, but at a slowly decreasing rate. Investigation showed that the ACTION command used to initiate the scram was inserting only one of the five simulated control rods banks, while the rest remained at their critical position of 53.5 inches. The model's reactor became momentarily subcritical, causing more primary system heat to be removed by the steam generator than was being input by the the reactor. This heat removal difference caused the small drop in primary system pressure between T=7 seconds and T=13 seconds. Because the primary coolant's average temperature dropped, the reactor returned to a critical condition due to the negative temperature coefficient of reactivity. At T=13 seconds, the heat removal rates were nearly equal, and pressure began to

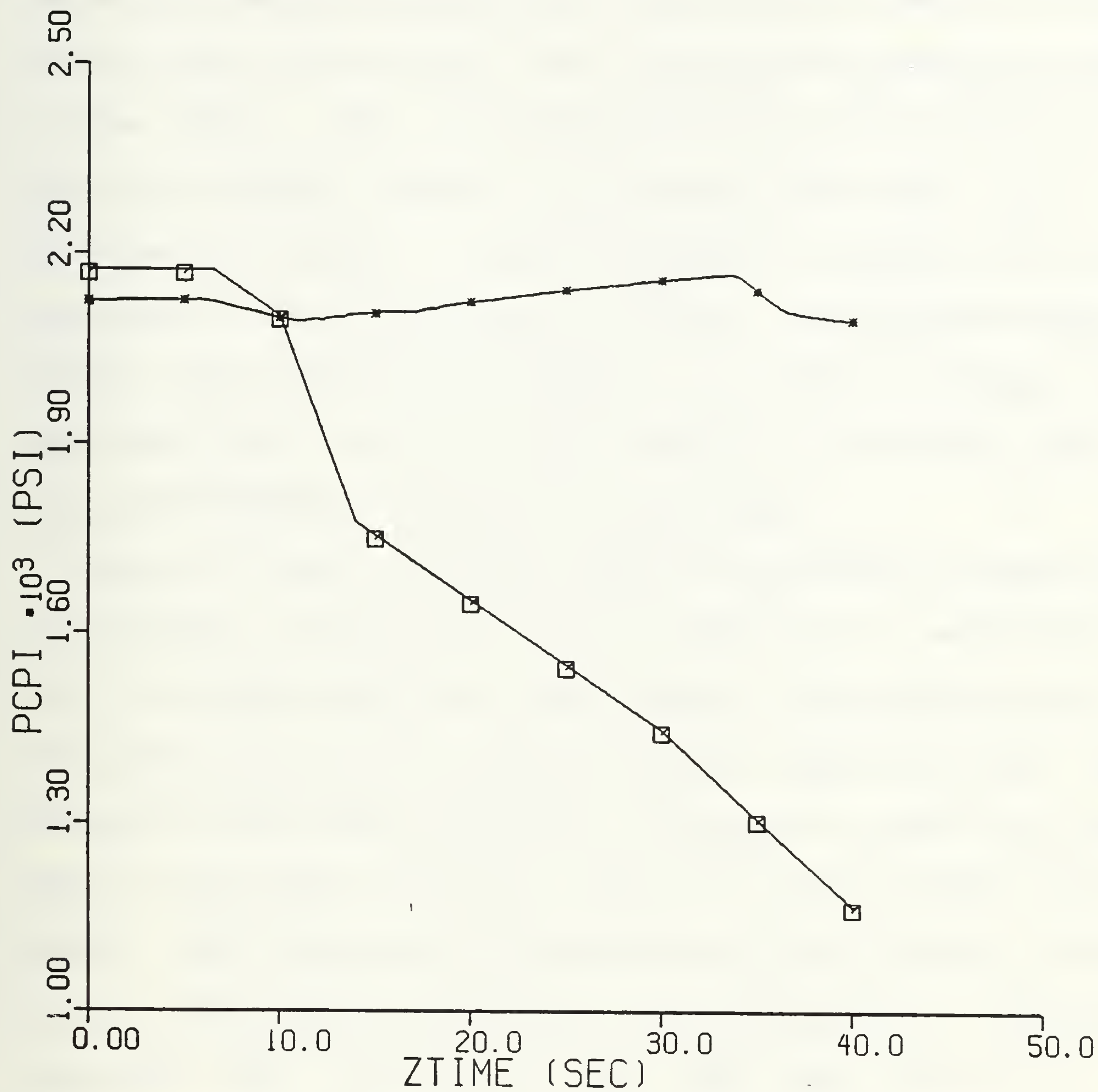


Figure 32: Unsatisfactory Performance: L3-5 Primary Pressure

increase because the backup heaters came on. Finally, when the backup heaters deenergized, the pressure began to fall quickly due to the coolant leak, causing the heaters to come on once again. This run demonstrated the unsuitability of using the ACTION command in changing the value of a subscripted variable. The rod heights of module RXX are contained in the five values of YRXX. The ACTION command changed only the value of YRXX(1). In order to change the remaining four values of this variable, the actual ACSL generated FORTRAN code had to be modified.

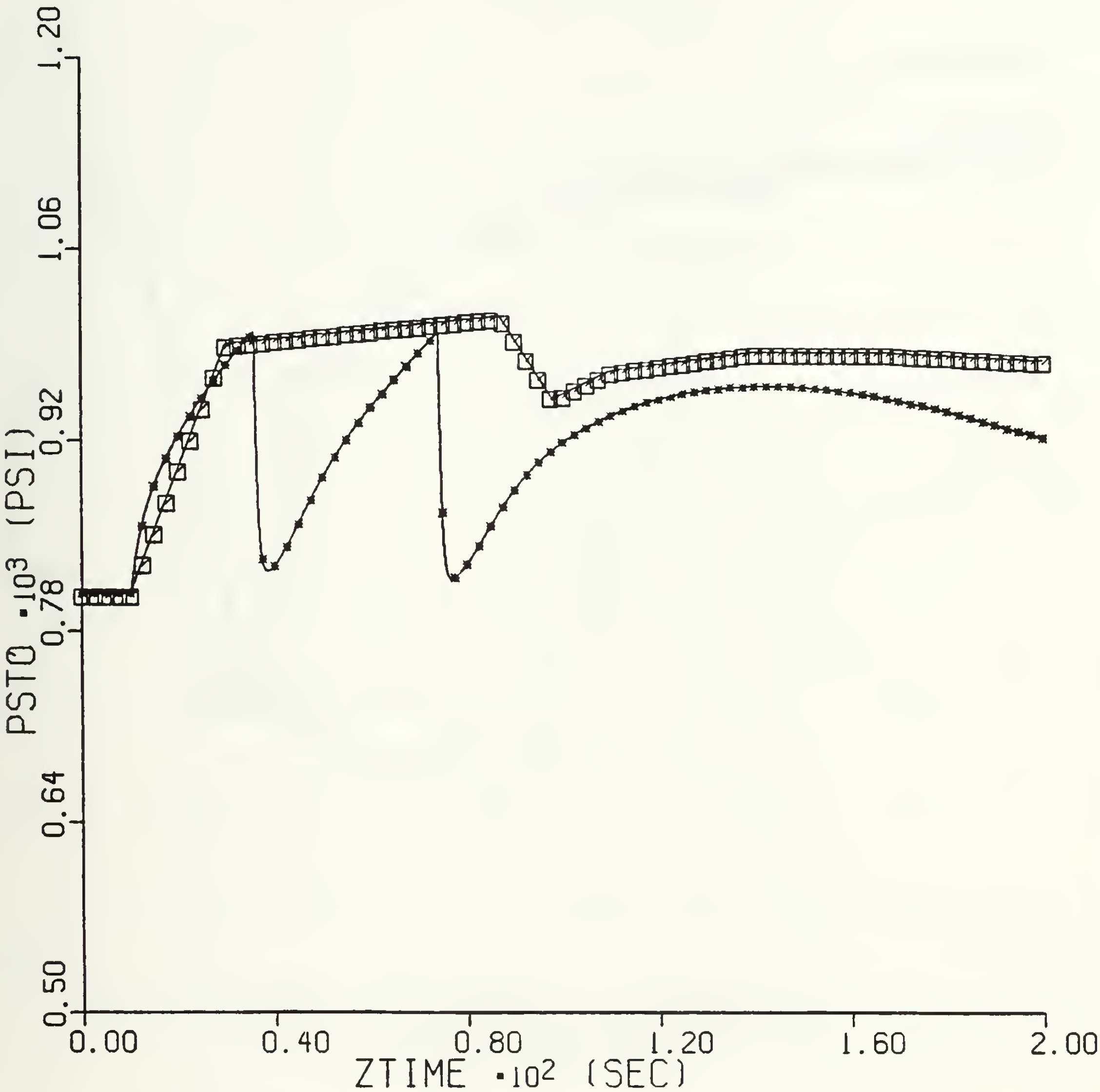
Figure 33 shows the steam generator secondary pressure of the facility, using the initial conditions of experiment L3-5. In this simulated run, however, the leak was not initiated, nor were the reactor coolant pumps secured. The pressure in the steam generator increases at nearly the same rate as the actual pressure, until the steam relief valve opened. The MMS valve was modeled as quick opening, since no other description was found in the references. This plot indicates that the actual valve has some level of accumulation, and does not fully relieve the pressure until it has reached a more fully open position. Hence the predicted pressure drops quickly upon opening the relief valve, and then builds up again when the valve shuts. Two valve operation cycles occur before the steam generator heat removal has been reduced to a point where the secondary pressure no longer reaches the valve's opening setpoint.

The final trends are similar to the actual changes in the LOFT facility steam generator pressure.

A number of L3-5 runs were made with varying primary system volumes and varying leak flow rates. The rate at which the coolant flowed through BRK had a direct impact on how fast the primary pressure dropped, as expected. It was also expected that changing the system volume would change the rate of depressurization. However, this was not the case. Even when the volume of the hot and cold legs was reduced to less than a tenth of the actual value, the rate of change of the pressure was not affected. The reason for this effect is unknown.

The effects of varying the flow rate of the high pressure injection pumps are shown in Figure 34. Here the initiation set point pressure was too low, moving the predicted pressure increase curve to the right of the actual curve. Once the HPI pumps did come on, however, they very quickly returned pressure to above the inital value, up to the automatic control band. This plot showed that the model's HPI flow rate was too high, and that the initiation set point pressure was too low.

Other output, such as the list file produed by every use of the ACSL was useful in the process of "zeroing in" the model to best predict the facility's performance. In particular, the DEBUG command, which provides a listing of most of the MMS internal variables, proved to be of great use in executing the models.



<u>Figure 33</u>: Unsatisfactory Performance: L3-5 Secondary Pressure

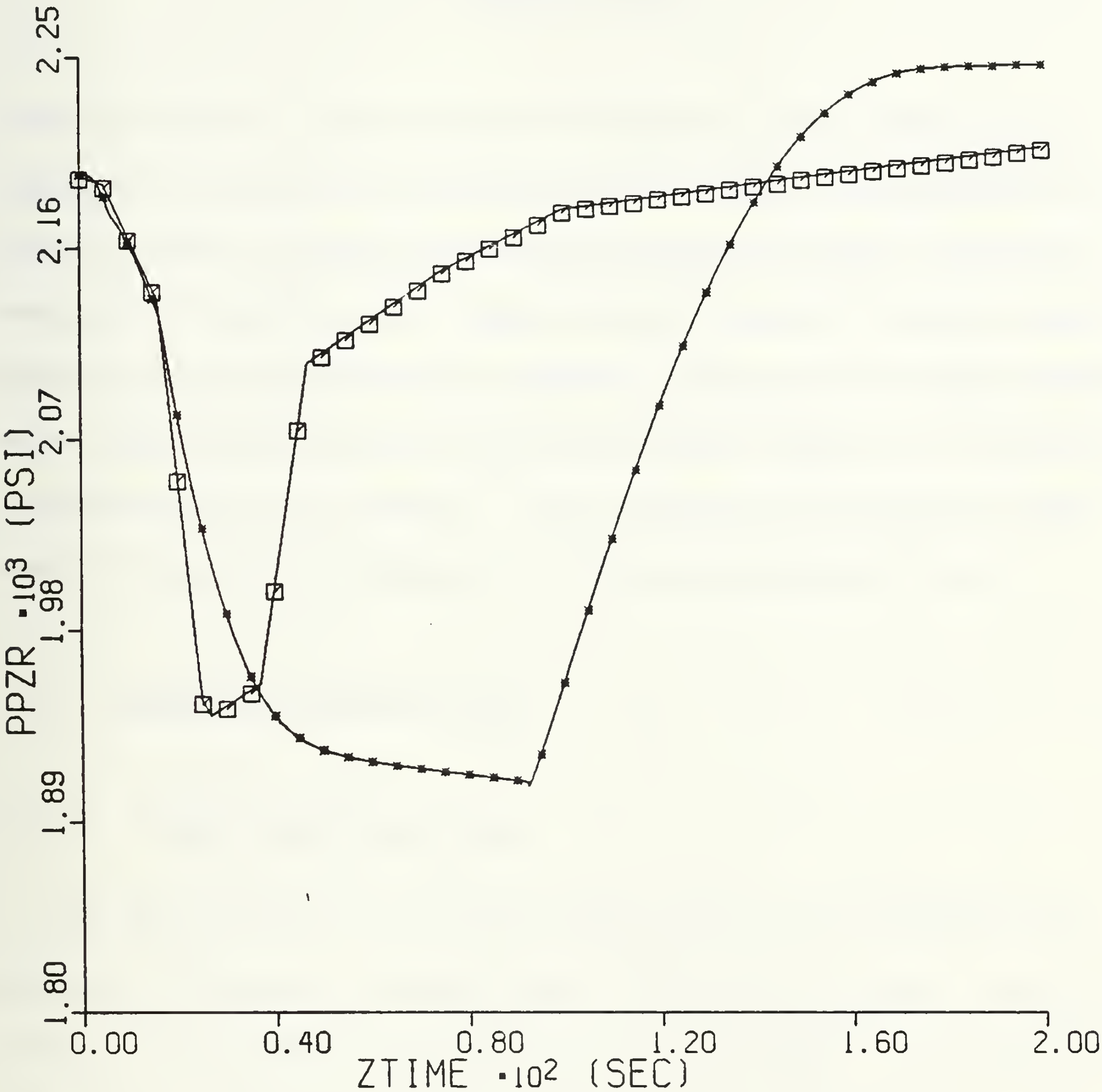


Figure 34: Unsatisfactory Performance: L6-3 Primary Pressure

Chapter 7

CONCLUSIONS

The results of the previous chapter give conflicting impressions about the ability of the MMS to successfully model a small pressurized water reactor plant transient. However, no mention was made of the reasons why the model did or did not perform as desired. Because the MMS worked under some conditions and did not under others, a variety of conclusions can be drawn. The failure to operate under severe transient conditions will be addressed first.

7.1 Causes of MMS Failure

7.1.1 Major Contributions

The MMS failed to operate past 30 real seconds when executing the L3-5 predictions. This failure was the most difficult problem encountered in this study. Determining the causes was the first step toward eliminating the problems, and proved useful in drawing conclusions about the MMS.

Reference [5] indicates that if saturation conditions are encountered in the reactor module, the module execution becomes unreliable. A review of the predicted conditions at all module junctions in the primary system model, as well as those within the reactor module itself, showed that no

saturation conditions were predicted before execution was halted. Thus an obvious cause of execution failure was eliminated.

When the valve module, FRV, controlled the feed flow, a command to shut this valve caused the upstream pressure to rise to the critical point. This is the point where the differences between the physical states of water become difficult to define. Here MMS execution becomes unreliable, but does not terminate. Eliminating the feed flow regulating valve module and its associated upstream connection module required that the feed flow itself be entered as a boundary condition. This eliminated some of the "pure modeling" done by the MMS. It did, however, solve the problem of reaching the critical pressure at the inlet to the feed regulating valve. Unfortunately, even without these modules, the model still would not operate past 30 real seconds.

A representative of the vendor which supplied the MMS recommended that the selected steam generator module used in the L3-5 configuration be replaced by the less capable UTSG module, using the configuration of Figure 15. This step, too, did not allow execution past the nominal 30 seconds. It was noted, however, that the "low order" steam generator module produced very similar predictions of steam generator pressure as did UTSGR.

Finally, attempts were made to piece the experiment together, one separate problem at a time. First, the reactor was shut down. As was shown in Figure 33, the model would operate under these conditions. (Operation was not very accurate, but it continued to the desired time.) Next the pump coastdown was added. In this case execution continued to almost 40 seconds of real time. The last attempt added the leak, but with the pumps left in operation. (This was experiment L3-6 at the LOFT facility.) Again, execution terminated at about 30 seconds. In the cases where the model would stop earlier than desired, the CPU time used was on the order of 25 seconds. In those cases where termination was at 200 seconds, CPU use was about 15 seconds.

The final factor considered in examining the L3-5 performance is the upturn in the pressurizer level in Figure 27. This sudden change cannot be explained by any physical phenomena, nor is it reflected in most of the other internal variables. Those variables that are affected are mostly pressurizer module variables, which are direct inputs to the differential equation matrix solving subroutine of the FORTRAN program. Except for this sudden change in pressurizer states, no unusual physical properties are seen. The predicted trends, although not accurate, do move in the expected directions.

In all the runs which terminated earlier than expected, the reason noted by the CMS operating system was a FORTRAN error code between 245 and 281. These are the codes which indicate an error in the use of double (or more) precision variables. The FORTRAN command which overrides these types of errors was ignored when executing under the ACSL structure.

When summed, these factors indicate that the MMS, using the Gear's Stiff algorithm, will continue to divide the differential time element until either the minimum allowed is reached or a FORTRAN problem with number precision is encountered. In none of the LOFT facility cases was execution ever terminated by reaching the minimum allowed time period. The problem is believed to be that some of the derivatives determined to apply to such short time intervals are recalculated enough times so that the storage locations assigned on the disk in use begin to overlap. This condition causes a FORTRAN interrupt.

On the other hand, it should be noted that the RX3 module allows very rapid changes in the level of reactor power, implying that large derivatives over small time intervals are allowed. Such a rapid change is seen in Figure 29. This change occurs so rapidly because power level is not a participant in the solution of the differential equations. The builders of the MMS instead used the concentration of delayed neutron precursors and decay heat causing fission

products as the values that are varied by differential equations. The power level is computed by a single FORTRAN statement, using the various reactivities from the rods, water temperature, and boron concentration directly. Hence, some variables can change almost instantaneously, while others cannot. A determination of which variables are of what type is required to learn if the model has stopped due to excessively large derivatives.

7.1.2 Minor Contributions

Problems with model parameterization were most evident in two recurring variables: pipe and valve flow conductances, and heat transfer parameters. In the case of the former, the conductance is typically determined by

$$FC = W/\rho(\Delta p)^{1/2} \qquad \text{Eqn. 7-1}$$

However, this equation yielded results sometimes far from the values eventually settled on by trial and error for use in the model. For example, in the hot leg piping, the actual pressure drop is 4 psia from the reactor outlet to the steam generator inlet. At a nominal density of 44 lbm/ft and flow rate of 3.78×10^6 lbm/hr, the flow conductance is 4.3×10^4. The value used in the model is 5.0×10^5 to arrive at the same flow rate and differential pressure. Although this variable was the source of some difficulty when initially setting up the steady states, it

did prove useful in varying flow rates through such valves as BRK.

In the case of the heat transfer coefficients, none proved more troublesome than those of the steam generator modules. After solving the series of equations provided in reference [5], again a trial-and-error process was needed to allow even the individual steam generator module to operate at the desired steady state. In UTSG, the final equation used for secondary heat transfer is

$$HTC = h_{boiling}/\Delta T_{LM} \exp(p_{sl}/630) \qquad \text{Eqn. 7-2}$$

Using as input the values of area, flow and water properties of references [7] and [12], this equation yields a value of 7.8. The value needed in the L6-3 model to achieve steady state is 10.0.

7.2 Satisfactory Results

In the case of experiment L6-3, the MMS clearly shows that it has a capability to predict small PWR plant performance under some conditions. The key features proven useful in this effort are the automatic control functions, of which there are many at both the LOFT facility and full sized plants, and the ability to easily change input data once a model has achieved steady state. (The subscripted variables described in Section 7.1.1 are the exception to this rule.)

The differences in the data of Figures 29, 30, and 31, while of substance, do not preclude the use of the MMS in performance predictions. When comparing the results of this study to the objectives of the MMS listed in Section 2.1, it is the author's conclusion that the MMS has a limited but reliable capability to model the thermal-hydraulic characteristics of a small-scale pressurized water reactor plant.

7.3 Comparison with Other Modeling Systems

Prediction data produced by the RELAP5/MOD1 code is available for experiment L3-5. This code successfully predicted the parameters of the LOFT facility well beyond the 200 second mark, so any comparison with the preformance of the MMS is very tenuous. In general, RELAP predicted the trends of the major parameters, but, similar to the MMS, at times the predicted and actual values were not close. RELAP5 is a very complicated code of over 200 FORTRAN subroutines, compared to the four used by the MMS. Because the MMS would not operate in a loss of fluid environment, RELAP5 proved the superior under these conditions.

RETRAN data is available for experiment L6-3. In this case the MMS did a better job of predicting the LOFT facility performance simply because it correctly predicted that the reactor would shutdown automatically on low primary

pressure. RETRAN, although predicting that steam flow rate would reach a steady state of 110% rated flow, reached a minimum pressure of only 2117 psia, just above the scram set point. The RETRAN "calculated heat transfer was less than in the experiment, causing the calculated cooldown to be less severe than measured."[11] The causes of the inaccurate heat transfer calculated by RETRAN were not described by Nalezny, but it can be assumed that improper parameterization was a contributing factor. All codes of this nature suffer from this problem, including the MMS.

No data are available on how much CPU time RELAP5 and RETRAN required when performing these specific predictions. It is safe to say they used much more than did the MMS, based on studies of references [10] and [13].

Use of the MMS complements, rather than replaces, the functions of these other more sophisticated computer codes. In arriving at general plant design parameters the MMS appears to be superior because of its relatively low computer costs and ease of operation. The prediction of actual severe transient performance for in-depth safety anaylsis is best left to the RELAP5/RETRAN series.

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[11] Nalezny, p. 9-19.

Chapter 8

RECOMMENDATIONS

In this study, the major questions left unanswered can be separated into three groups: how do the volume calculations affect the MMS's performance?; what are the time limits to which a moderately severe transient can be predicted?; and what is the solution to the FORTRAN digit precision problem?

Although there are thermodynamic problems with the MMS other than those caused by poor volume calculations, the effects of this parameter being determined incorrectly are of immediate concern. As the problem with the leak flow rate in experiment L3-5 showed, the total mass inventory does not seem to be a factor when calculating pressure changes. Instead, fluid masses seem to be a module specific characteristic. Further, this characteristic appears to apply to only the storage modules. As was noted in Chapter 6, changing the volume of the purely resistive pipe modules had no effect on the rate of pressure change, while the flow rate out of the leak had a profound effect. Before further use of the MMS can be made in investigating accidents which involve loss of mass inventory, the method of determining the inventory must be corrected. The first efforts in this direction should be to vary the flow from a simple storage model, for example the stand alone pressurizer of reference [6].

Finding the time limits of the MMS would seem to be a simple problem. The difficulty, is introduced, of course, by also finding the limits of transient severity which the MMS can endure. Since at the 200 second point of experiment L6-3 the LOFT facility had returned to near steady state, the "severity limit" can be initially placed between that caused by a rapid increase in steam demand, and that caused by a small break loss of coolant. The LOFT facility's series of experiments is ideal for use in such a determination. The actual experimental results are available from a variety of sources in both raw and fully interpreted forms. Other transient predictions which the MMS has performed accurately on full-scale plants such as the Peach Bottom turbine trip can be extended to include those performed at the LOFT facility. Since there are currently a variety of steam generator, pressurizer, reactor, and pump modules available, the best combination for each type of transient needs to be determined to utilize the fullest potential of the MMS.

Investigating the problem of the FORTRAN interrupts requires a joint effort of nuclear and systems engineers. Whether or not to place a high priority on this problem is also a matter of question. Since there are codes now available which have the capabilities that the MMS showed in this study, solving this problem involves trading off the cost with the expected benefits.

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Appendix A

LIST OF SYMBOLS

t - time

e - flow entering a module (subscript)

w - mass flow rate

i,j - direction vectors (subscript)

e - energy per unit mass

W - work rate

g_c - dimensional constant

g - gravitational acceleration

q - heat transfer rate

A - heat tranfer area

h - enthalpy

L - length

$\int_V$ - volume integral

ϕ - any thermodynamic property

A - area vector

H - total enthalpy

R - reverse flow

β - effective delayed neutron fraction

j - delayed neutron group (subscript)

D - neutrons passing between adjacent nodes

I - reactivity term

ρ - density

l - flow leaving a module (subscript)

V - volume

V - velocity

q''' - heat generation per unit volume per unit time

σ - shear stress

p - pressure

θ - angle between flow path and a horizontal plane

U - heat transfer coefficient or internal energy

T - temperature

f - friction factor

D - diameter

$\int_s$ - surface integral

s - surface (subscript)

M - mass

α_h - partial of density with respect to enthalpy at constant pressure

α_p - partial of density with respect to pressure at constant enthalpy

z - thermodynamic property relationship term

1,2 - adjacent control volume (subscript)

n_i - number of neutrons in node i

Λ - neutron generation time

C_{ji} - delayed neutron precursors in group j and node i

k,i - node indicator (subscript)

λ - delayed neutron group decay constant

J_c - Joule's constant

$$f_n = \begin{cases} 0, & w_n < 0 \\ 1, & w_n > 0 \end{cases}$$

Appendix B

THERMAL-HYDRAULIC COMPONENTS AND NAMES

Reactor	- RXX
Pressurizer	- PZR
Pipes:	
hot leg	- RXO
cold leg	- SGP
additional hot leg for L6-3	- SSG
Valves:	
spray	- PSY
pressurizer relief	- REL
main steam control	- MSS
main stem relief	- MSR
HPIS inlet	- XC
simulated break	- BRK
feedwater regulating	- FRV
Surge junction	- SUR
Reactor coolant pumps	- RCP

Steam generator:

experiment L3-5 - ITL

experiment L6-3 - ITL

Connections:

coolant pump discharge to reactor inlet - PRX

feedwater inlet - RFW

HPIS junction - XCI

Flow dividers:

cold leg/break/spray - RXI

steam control valve inlet - MSL

Appendix C

MMS/ACSL MODEL FILE STRUCTURE

```
PROGRAM TRANS
DYNAMIC
    LOGICAL OMASK
    CINTERVAL CINT = .1
    NSTEPS    NSTP = 100000
    MAXTERVAL MAXT = 100.
    ALGORITHM IALG = 2
    CONSTANT TSTOP = 10.    ,...
             OMASK = .TRUE.
    TERMT(T.GE.TSTOP)
' '
' '
DERIVATIVE
' '
'   START TRANSIENT CLOCK WHEN TRANS=.TRUE.  '
   LOGICAL  TRANS
   CONSTANT TRANS=.FALSE.
    PROCEDURAL (ZTIME=T,TRANS)
      ZTIME=0.
      IF (TRANS) ZTIME=T
' '
TABLE
HANRCP,1,6/0.,.2,.4,.6,.8,1.,1.4,1.36,1.31,1.23,1.13,1./
TABLE HVNRCP,1,8/0.,.143,.286,.429,.571,.714,.857,1., ...
                    -.68,-.56,-.42,-.23,-.03,.2,.57,1./
TABLE HADRCP,1,6/-1.,-.8,-.6,-.4,-.2,0.,2.54,2.03,1.82,1.61,
...
                 1.48,1.4/
TABLE HVDRCP,1,8/-1.,-.857,-.714,-.571,-.429,-.286,-.143,0.,
...
                    2.54,2.06,1.73,1.48,1.29,1.18,1.07,.93/
TABLE
HATRCP,1,7/0.,.2,.4,.4,.6,.8,1.,.25,.28,.33,.27,.47,.71,1./
TABLE HVTRCP,1,10/0.,.11,.22,.33,.44,.55,.66,.77,.88,1., ...
                .93,.91,.89,.87,.83,.83,.84,.85,.89,1./
TABLE HARRCP,1,6/-1.,-.8,-.6,-.4,-.2,0.,-1.,-.6,-.3, ...
                    .05,.13,.25/
TABLE HVRRCP,1,6/-1.,-.8,-.6,-.4,-.2,0.,-1.,-.97,-.93, ...
                    -.88,-.79,-.68/
TABLE TANRCP,1,6/0.,.2,.4,.6,.8,1.,.6,.63,.73,.83,.92,1./
```

```
TABLE TVNRCP,1,7/0.,.2,.4,.5,.6,.8,1.,-.48,-.36,-.26,.12,.3,
...
                        .64,1./
TABLE
TADRCP,1,6/-1.,-.8,-.6,-.4,-.2,0.,2.,1.39,1.04,.8,.67,.6/
TABLE TVDRCP,1,8/-1.,-.9,-.7,-.5,-.4,-.2,-.1,0., ...
              2.,1.9,1.73,1.58,1.52,1.38,1.35,1.26/
TABLE TATRCP,1,4/0.,.4,.5,1.,-.68,-.27,0.,.34/
TABLE TVTRCP,1,10/0.,.11,.22,.33,.44,.55,.66,.77,.89,1., ...
                1.26,1.17,1.07,.98,.9,.78,.67,.55,.44,.34/
TABLE TARRCP,1,4/-1.,-.4,-.1,0.,-1.,-.91,-.52,-.48/
TABLE TVRRCP,1,4/-1.,-.4,-.07,0.,-1.,-.91,-.8,-.67/
TABLE IANRCP,1,7/0.,.12,.22,.5,.7,.91,1.,0.,.85,1.09,1.02,
...
                1.,.94,1./
TABLE IVNRCP,1,8/0.,.1,.2,.3,.5,.7,.9,1.,0.,-.02,.01,.09,
...
                .31,.55,.77,1./
TABLE IADRCP,1,10/-1.,-.9,-.7,-.6,-.5,-.4,-.3,-.2,-.1,0.,
...
                -1.17,-1.23,-2.3,-2.8,-2.92,-2.68,-2.,
...
                -1.35,-.7,0./
TABLE IVDRCP,1,10/-1.,-.9,-.8,-.7,-.6,-.5,-.4,-.3,-.2,0.,
...
           -1.17,-.59,-.52,-.32,-.19,-.1,-.03,.01,.04,.1/
TABLE IATRCP,1,6/0.,.2,.4,.6,.8,1.,0.,-.33,-.65,-.94, ...
               -1.2,-1.47/
TABLE IVTRCP,1,10/0.,.1,.2,.3,.4,.5,.6,.7,.85,1.,.1,.13,.15,
...
                .15,.12,.07,-.04,-.25,-.7,-1.42/
TABLE IARRCP,1,6/-1.,-.8,-.6,-.4,-.2,0.,-1.17,-.52,-.2, ...
                -.03,.05,.1/
TABLE IVRRCP,1,6/-1.,-.8,-.6,-.4,-.2,0.,-1.17,-.52,-.2, ...
                -.03,.05,.1/
TABLE UANRCP,1,6/0.,.2,.4,.6,.8,1.,.6,.63,.73,.83,.92,1./
TABLE UVNRCP,1,7/0.,.2,.4,.5,.6,.8,1.,-.48,-.36,-.26,.12,.3,
...
                          .64,1./
TABLE
UADRCP,1,6/-1.,-.8,-.6,-.4,-.2,0.,2.,1.39,1.04,.8,.67,.6/
TABLE UVDRCP,1,8/-1.,-.9,-.7,-.5,-.4,-.2,-.1,0., ...
              2.,1.9,1.73,1.58,1.52,1.38,1.35,1.26/
TABLE UATRCP,1,4/0.,.4,.5,1.,-.68,-.27,0.,.34/
TABLE UVTRCP,1,10/0.,.11,.22,.33,.44,.55,.66,.77,.89,1., ...
                1.26,1.17,1.07,.98,.9,.78,.67,.55,.44,.34/
TABLE UARRCP,1,4/-1.,-.4,-.1,0.,-1.,-.91,-.52,-.48/
TABLE UVRRCP,1,4/-1.,-.4,-.07,0.,-1.,-.91,-.8,-.67/
TABLE HMTRCP,1,13/0.,.05,.1,.15,.2,.3,.4,.5,.6,.7,.8,.9,1.,
...
              0.,0.,.03,.08,.17,.47,.63,.73,.81,.85, ...
                .83,.71,.08/
```

```
TABLE
TMTRCP,1,7/.1,.3,.4,.5,.6,.7,1.,0.,.24,.31,.33,.3,.24,0./
' '
  PUMP4Q('RCP','CPI','RCPO',0,0)
' '
    CONSTANT KKVRCP = 1.5E-5
    CONSTANT KNPRCP = 2.
    CONSTANT KNRRCP = 3530.
    CONSTANT KQRRCP = 5000.
    CONSTANT KPRRCP = 315.
    CONSTANT KTRRCP = 369.
    CONSTANT KVPRCP = 3.5
    CONSTANT KRRRCP = 38.31
' '
   CONNI('PRX','CPO','PORI')
' '
   PIPER('SGP','SGO','CPI',0,0,1)
' '
    CONSTANT      KCKSGP = .TRUE. ,    KCFSGP = 3.08E5 , ...
                  KDHSGP = 0. ,        KLPSGP = 33.69 , ...
                  KAFSGP = .6827 ,     KVPSGP = 23. , ...
                  IHCPI = 540.
' '
' '
DIV('RXI','PORI','CLI1','CLI2','CLB1','CLB2','PZSP','BRAK')
' '
     VALVEI('PSY','PZSP','PSP')
       CONSTANT  KCPPSY=9.E66, KCVPSY=241.4, ...
                 KCKPSY=.TRUE.,  KDHPSY=10.73 , KVAPSY = 3
' '
   VALVED('BRK','BRAK','BRST')
' '
    CONSTANT      KCKBRK = .TRUE. ,      KCVBRK = 300.   ,
...
                                       KKMBRK = 1., ...
                  KVABRK = 3.
' '
  TABLE KF1RXX,1,8/0.,25.,33.3,40.,50.,66.7,75.,100.,...
               1.,.347,.125,-0.008,-0.115,-0.103,-0.046,0./
  TABLE KF2RXX,1,8/0.,25.,33.3,40.,50.,66.7,75.,100.,...
                   1.,1.025,.843,.683,.423,.094,.012,0./
  TABLE KF3RXX,1,8/0.,25.,33.3,40.,50.,66.7,75.,100.,...
                    1.,1.019,.977,.956,1.007,.778,.596,0./
' '
  TABLE KRERXX,1,3/0.,.5,1.,1.,1.22,1.4/
' '
  TABLE KR1RXX,1,3/0.,50.,100.,2258.,2258.,2258./
  TABLE KR2RXX,1,3/0.,50.,100.,2258.,2258.,2258./
  TABLE KR3RXX,1,3/0.,50.,100.,2258.,2258.,2258./
  TABLE KR4RXX,1,3/0.,50.,100.,2258.,2258.,2258./
' '
  TABLE KP1RXX,1,8/0.,12.,25.0,42.,52.,62.0,76.,100.,...
                1.66,2.10,2.04,0.12,-0.16,-0.13,0.12,0./
  TABLE KP2RXX,1,8/0.,20.,38.0,48.,60.,74.0,86.,100.,...
```

```
                    0.28,1.12,1.33,1.22,.86,.27,-.03,0./
  TABLE KP3RXX,1,6/0.,24.,32.0,50.,67.0,100.,...
                    .1,-.2,0.,1.98,1.88,0./
' '
  TABLE KL1RXX,1,3/0.,50.,100.,25521.15,25521.15,25521.15/
  TABLE KL2RXX,1,3/0.,50.,100.,26031.5 ,26031.5 ,26031.5 /
  TABLE KL3RXX,1,3/0.,50.,100.,33153.9,33153.9,33153.9/
' '
RX3('RXX','CLI1','CLI2','CLB1','CLB2','HLI1','HLB1', ...
    'BOR',0,0,0)
' '
  CONSTANT GBOR   = 1345.
  CONSTANT KBBRXX=.000209,.001416,.001309,.002727,...
                    .000935,.000314
  CONSTANT KBERXX=.000209,.001416,.001309,.002727,...
                    .000935,.000314
  CONSTANT KCCRXX = .008
  CONSTANT KCMRXX = 82.
  CONSTANT KD1RXX = .43908,KD2RXX = .37078,KD3RXX=.19014
  CONSTANT KD5RXX = -2.619 ,              KD6RXX = -.00423
  CONSTANT KD7RXX = 3.68E-4 ,             KD8RXX = 8.66E-7
  CONSTANT KEPRXX = 7.   ,KFCRXX = 5.4E4
  CONSTANT KFFRXX = 1.4E5
  CONSTANT KGDRXX = 3.17, 2.14 , 3.57,    KGIRXX = 1.547E9
  CONSTANT KLBRXX =.0125,.0308,.114,.307,1.19,3.19
  CONSTANT KLCRXX = 5.5 , KLDRXX = 5.55E-2 , 4.3E-3 ,
6.66E-5
  CONSTANT KLERXX = .0125 , .0308 , .114 , .307 , 1.19 ,
3.19
  CONSTANT KLIRXX = 2.85E-5 ,             KLPRXX = 6.45
  CONSTANT KLTRXX = 11.95 ,               KLXRXX = 2.10E-5
  CONSTANT KMBRXX = 308.    ,-9.    ,0.    ,0.          ,...
                     -3     ,-2.0E-2,0.    ,0.          ,...
                     0.,0.,0.
  CONSTANT KMXRXX = 1.     ,              KRPRXX = 2258.
  CONSTANT KM2RXX = -10.293 ,             KM3RXX = 0.0126
  CONSTANT KTSRXX = .5
  CONSTANT KT1RXX = 3.08 ,                KT2RXX = .07
  CONSTANT KVBRXX = 43.94,KVRRXX = 3.5,   KVTRXX = 31.63
  CONSTANT K04RXX = 0.217 ,               K1XRXX = 4.9117E7
  CONSTANT K10RXX = 134.01 ,              K14RXX = 2.767
  CONSTANT K2XRXX = 6.3210E-7 ,           K23RXX = 8.276E-4
  CONSTANT K3XRXX = -1.387E-12 ,          ZRORXX = 0.,0.,0. ,
...
  YRXX = 81.,81.,81.,81.,81.
' '
'INITIAL CONDITIONS '
' '
CONSTANT  ZIPRXX = 15059 , 46106 , 2912 , 17039 , ...
                   52156 , 3295,21043,64398,4067, ...
          ZIFRXX = 800. , 900. , 1100. , ...
          ZIHRXX = 552.7 , 568.4 , 584.9 , ...
          ZIDRXX = 5715. , 5.45E4, 2.E6  , ...
```

```
          IHURXX = 585.1 ,                IPHLI1 = 2155.8  ,
...
          ZPIRXX = 2175.0 ,               ZHSRXX = 540.0, ...
          ZIXRXX = 2.0E15 , 1.8E15 , 1.9E15, ...
          ZIIRXX = 5.9E15, 4.9E15 , 5.5E15
' '
' BOUNDARY CONDITIONS '
   CONSTANT WHLB1 = 0.
''
  POWER = ZATRXX/1.1
' '
  PIPER('RXO','HLI1','HLI2',0,0,1)
' '
   CONSTANT      KCKRXO = .FALSE. ,  KCFRXO = 5.0E5 , ...
                 KDHRXO = 0. ,       KAFRXO = .6827 , ...
                 KVPRXO = 13.56 ,    KLPRXO = 19.86 , ...
                 IHHLI2 = 585.1
''
  SURJNC('SUR','HLI2','SGI','PSG')
    CONSTANT IPHLI2=2154.8,  KVTSUR=.44
''
  PZRB('PZR','PSG','PSP','PRF','EHTRS',3)
' '
  CONSTANT  KLHPZR = 1.25,      KRCPZR = 1.417 ,...
            KLTPZR = 5. ,       KLRPZR = .729 , ...
            KLSPZR = 6.917 ,    KLUPZR = 1.083 , ...
            KLBPZR = .708 ,     KAPPZR = 13.4 , ...
            KACPZR = 6.31 ,     KATPZR = 71.3 , ...
            KVHPZR = 3.8 ,      KVTPZR = 39.15 ,...
            KUIPZR = 3. ,       KUCPZR = 110. , ...
            KUDPZR = 40. ,      KULPZR = 90. , ...
            KCWPZR = .006 ,     KCFPZR = .56 , ...
            KCGPZR = .47 ,      KLLPZR = .5 , ...
            KUTPZR = 6.27
   'INITIAL CONDITIONS'
    CONSTANT IPPZR=2154.8         , ...
             ZIMPZR=838.9         , ...
             ZITPZR=646.8,646.8   , ...
             IHPZR = 690.07,1124.00
''
   VALVED('REL','PRF','OUT')
     CONSTANT KCVREL=97.,   KVAREL=3 ,  KKMREL=1.0
     CONSTANT KCKREL=.TRUE.
' '
     'BOUNDARY CONDITIONS'
      CONSTANT POUT=14.7
''
TABLE KCPITL,1,4/400.,450.,500.,520.,1.075,1.12,1.175,1.21/
' '
TABLE KMCITL,1,2/400.,550.,.113,.113/
' '
TABLE KMRITL,1,2/400.,550.,480.,480./
' '
TABLE KMTITL,1,2/400.,550.,23.7,23.7/
```

```
' '
TABLE KTCITL,1,4/400.,450.,500.,520.,1.07E-4,1.04E-4, ...
                 9.9E-5,9.6E-5/
' '
TABLE KVFITL,1,4/400.,450.,500.,520.,9.12E-5,8.05E-5, ...
                 7.17E-5,6.9E-5/
' '
UTSGR ('ITL','SGI','SGO','FWI','STO',0,0,0)
' '
   CONSTANT KAPITL = 1.626 ,
            KASITL = 6.21,3.63,17.63,2.5,...
            KCFITL = 1.385E4 ,        KDPITL = .0335 , ...
            KDSITL = .05000 ,         KHPITL = .5,.5,.5,.5,
...
            KHSITL = .5,.5 ,          KHBITL = .6,.6 , ...
            KRPITL = .5,.5,.5,.5,     KRDITL = .0082 , ...
            KPMITL = 194.2 ,          KMSITL = 241.5 , ...
            KPAITL = 205.8,229.5,217.85 , ...
            KAIITL =
1.5,1.5,1.5,1.5,1.,1.,1.,1.,1.,1.,1.,4., ...
            KLIITL =
.175,.36,.545,.735,1.,1.,1.,1.,1.,1.,1.6 , ...
            KAGITL = 32.2 , ...
            KLHITL = 7.04 ,           KLTITL = 20. , ...
            KNDITL = 0.5 ,            KVTITL = 146. , ...
            KCOITL = 1.2 ,            KJOITL = 778.2 , ...
            KSLITL = 1. ,             KSTITL = .0524
' '
' INITIAL CONDITIONS '
' '
 CONSTANT ILSITL = 2.5,4.00 ,    ILBITL = 6.4 , ...
          ILDITL = 10.4 ,        IH3ITL = 575.0 , ...
          IH7ITL = 553.2 ,       IH4ITL = 542.5 , ...
          IHSGO  = 540.0 ,       IH1ITL = 581.6 , ...
          IH2ITL = 543.5 ,       IHDITL = 485.5 , ...
          IPUITL = 808. ,        ITMITL = 560.,533.,536.0,
...
                                          533.5 , ...
          IPSGO  = 2123.3,       IWDITL = 750.00
''
   'HEATER AND SPRAY CONTROLLER'
''
       'TOTAL HEATER INPUT'
        EEHTRS = EHT1+EHT2
''
     ONOFF('HT1',PPZR,EHT1)
       CONSTANT  KONHT1=2235.,KVNHT1=12. ,...
                 KOFHT1=2265.,KVFHT1=0.
''
     ONOFF('HT2',PPZR,EHT2)
       CONSTANT  KONHT2=2230.,KVNHT2=36. ,...
                 KOFHT2=2245.,KVFHT2=0.
''
     ONOFF('SVC',PPZR,CYPSY)
```

```
       CONSTANT  KONSVC=2275.,KVNSVC=1.0,...
                 KOFSVC=2250.,KVFSVC=0.0
''
     ACT('PSY')
       CONSTANT  KATPSY=2.0, KTCPSY=1.0
''
     ONOFF('RVC',PPZR,CYREL)
        CONSTANT KONRVC=2410.,  KVNRVC=1.0
        CONSTANT KOFRVC=2390.,  KVFRVC=0.0
''
     ACT('REL')
       CONSTANT  KATREL=2.0, KTCREL=3.0
       CONSTANT IYREL=0.0
''
 VALVEC('MSS','STO3','STO1')
  CONSTANT KCKMSS = .TRUE. ,KCVMSS = 1.E5 ,KVAMSS = 3 ,...
              KVCMSS = 2000. , KXTMSS = 1.
' '
 VALVEC('MSR','STO4','STO2')
  CONSTANT KCKMSR = .TRUE. ,KCVMSR = 1.E5 ,KVAMSR = 3 ,...
              KVCMSR = 2000. , KXTMSR = 1.
' '
 ONOFF('MSC',PSTO,CYMSR)
  CONSTANT  KONMSC=1000.,KVNMSC=1.0,...
             KOFMSC= 970.,KVFMSC=0.0
' '
 ACT('MSR')
  CONSTANT  KATMSR=2.0, KTCMSR=3.0
' '
 ONOFF('XCC',PPZR,CYXC)
  CONSTANT  KONXCC=1909.,KVNXCC=1.0,...
                 KOFXCC=2250.,KVFXCC=0.0
''
 ACT('XC')
  CONSTANT  KATXC=2.0, KTCXC=3.0
''
 JUNC('XCI','CPO','HPI','RCPO')
' '
 VALVEI('XC','HPA','HPI')
  CONSTANT  KCPXC =250. , KCVXC = 250., HHPA = 70. , ...
          KCKXC =.TRUE.,  KDHXC =10.73 , KVAXC  = 3
  PHPA = PCPO+20.
''
 DIV('MSL','STO','STO3','STO4')
' '
 VALVEI('FRV','FWI1','FWI')
  CONSTANT  KCPFRV=1.E4 , KCVFRV=1.E4 , ...
       KCKFRV=.TRUE.,  KDHFRV= 0.   , KVAFRV = 3
' '
   CONNI('RFW','FWI2','FWI1')
       CONSTANT WFWI2 = 202500.
TABLE BY1,1,4/0.,5.2,7.2,10000.,81.,81.,0.,0./
TABLE BY2,1,4/0.,5.2,7.2,10000.,81.,81.,0.,0./
TABLE BY3,1,4/0.,5.2,7.2,10000.,81.,81.,0.,0./
```

```
TABLE BY4,1,4/0.,5.2,7.2,10000.,81.,81.,0.,0./
TABLE BY5,1,4/0.,5.2,7.2,10000.,81.,81.,0.,0./
TABLE BREAK,1,4/0.,9.99,10.,10000.,0.,0.,1.,1./
TABLE STEAM,1,4/0.,6.2,16.2,200.,1.,1.,0.,0./
TABLE FEED,1,4/0.,6.2,7.2,10000.,1.,1.,0.,0./
TABLE PMPSD,1,7/0.,10.8,15.8,20.8,25.8,30.8,39.3, ...
                  3025.,3025.,2087.,1528.,1089.,696.,0./
TABLE ACTFLW,1,10/0.,10.8,20.,25.,30.,35.,40.,100., ...
        150.,10000., ...
        3.78E6,3.78E6,1.78E6,1.19E6,8.71E5,4.51E5, ...
        4.11E5,4.51E5,4.04E5,3.96E5/
TABLE PRZLVL,1,5/0.,6.5,11.,34.,10000.,4.24,4.24,4.,0.,0./
TABLE CLDPRS,1,10/0.,6.5,10.,14.,30.,40.,55.,87., ...
        110.,10000., ...
        2175.,2175.,2103.,1777.,1450.,1170.,1088., ...
        1059.,1015.,14.7/
TABLE SGPRES,1,9/0.,7.,30.,87.,98.,110.,140., ...
        165.,2900., ...
        808.,808.,991.,1012.,951.,972.,986.,986.,509./
BSGPRS = SGPRES(ZTIME)
BPRIFL = ACTFLW(ZTIME)
BLEVEL = PRZLVL(ZTIME)
BCLPRS = CLDPRS(ZTIME)
BSPD=PMPSD(ZTIME)
BFEED=FEED(ZTIME)
BSTEAM=STEAM(ZTIME)
Y1=BY1(ZTIME)
Y2=BY2(ZTIME)
Y3=BY3(ZTIME)
Y4=BY4(ZTIME)
Y5=BY5(ZTIME)
BBREAK=BREAK(ZTIME)
PROCEDURAL (YFRV = BFEED)
   YFRV = BFEED
END $ 'OF PROCEDURAL (YFRV)'
PROCEDURAL (RFLOW=BPRIFL)
  RFLOW = BPRIFL
END $ 'OF PROCEDURAL (RFLOW)'
PROCEDURAL (RLEVEL = BLEVEL)
  RLEVEL = BLEVEL
END $ 'OF PROCEDURAL (RLEVEL)'
PROCEDURAL (RCLPRS = BCLPRS)
  RCLPRS = BCLPRS
END $ 'OF PROCEDURAL (RCLPRS)'
PROCEDURAL (RSGPRS = BSGPRS)
  RSGPRS = BSGPRS
END $ 'OF PROCEDURAL (RSGPRS)'
PROCEDURAL (NRCP = BSPD)
   NRCP = BSPD
END $ 'OF PROCEDURAL (NRCP)'
PROCEDURAL (YMSS = BSTEAM)
   YMSS = BSTEAM
END $ 'OF PROCEDURAL (YMSS)'
PROCEDURAL (YBRK = BBREAK)
```

```
   YBRK = BBREAK
END $ 'OF PROCEDURAL (YBRK)'
PROCEDURAL (YRX = Y1,Y2,Y3,Y4,Y5)
   YRXX(1)=Y1
   YRXX(2)=Y2
   YRXX(3)=Y3
   YRXX(4)=Y4
   YRXX(5)=Y5
END $ 'OF PROCEDURAL (YRX)'
INTEGER COUNT, KOUNT
PROCEDURAL(COUNT=)
 CONSTANT COUNT=0,KOUNT=1000
 COUNT=COUNT+1
 TERMT(COUNT.GE.KOUNT)
END $ ' OF PROCEDURAL '
   END $ ' OF DERIVATIVE '
 END $ ' OF DYNAMIC '
END $ ' OF PROGRAM '
```

Appendix D

MMS/ACSL COMMAND FILE STRUCTURE

```
SET TITLE="LOFT REACTOR STEADY STATE"
SET TCWPRN=72 , TJNITG = 1.E66,PRN=9  ,IALG=2
SET KM2RXX = -10.3
SET ZIPRXX = 15204,50370,3247,16942,54825         , ...
            3517,2062565450,4180                  , ...
    IHCPI  = 539.69       ,   KCFSUR = 1.E5    , ...
    KCFITL = 9.70E4       ,   IPCPI  = 2121.7  , ...
    IW1RCP = 1.89E6       ,   IPPORI = 2179.5  , ...
    WFWI2  = 2.205E5      ,   PSTO1  = 2.205E5, ...
    RFWI2  = 51.73        ,   TFWI2  = 449.7   , ...
    PSTO2  = 808.         ,   IPFWI1 = 809.    , ...
    PFWI2  = 809.         ,   HFWI2  = 425.    , ...
    WSTO   = 2.205E5      ,   WFWI1  = 220500  , ...
    WFWI   = 220500       ,   HFWI   = 425.18  , ...
    YREL   = 0.           ,   WSGI   = 3.78E6  , ...
    YBRK   = 0.           ,   KVCPSY = 2000.   , ...
    KVCBRK = 2000.        ,   KVCREL = 2000.   , ...
    KVCFRV = 2000.        ,   N      = 1       , ...
    PBRST  = 14.7         ,   IYPSY  = 0.      , ...
    IYMSR  = 0.           ,   PPSG   = 2152.   , ...
    ZHGPSY = 1123.7       ,   ZRFPSY = 37.73   , ...
    ZRGPSY = 5.78         ,   KCPPSY = 120.    , ...
    KPMITL = 97.          ,   KPAITL = 104.,116.,110. , ...
    KMSITL = 122.         ,   ILSITL = 4.6242,6.8561  , ...
    ILDITL = 10.5         ,   IH3ITL = 577.74  , ...
    IH7ITL = 539.17       ,   IH4ITL = 537.26  , ...
    IHSGO  = 540.         ,   IH1ITL = 846.752, ...
    IH1ITL = 846.752      ,   IH2ITL = 567.75  , ...
    IHDITL = 482.47       ,   IPUITL = 808.    , ...
    ITMITL = 572.9,537.81,524.27,520.25        , ...
    IPSGO  = 2123.3       ,   IWDITL = 350.17  , ...
    IPPZR  = 2152.        ,   ZPIRXX = 2175.   , ...
    IPHLI1 = 2153.        ,   IPHLI2 = 2152.1  , ...
    KASITL = 4.5 ,15.,17.6,2.55                , ...
    KCVMSS = 1.E6         ,   KVCXC  = 2000. , ...
    RHPA   = 62.11        ,   YXC    = 0.    , ...
    IYXC   = 0.
PROCED NULL
SET NDBUG=1,TSTOP =750.,CINT = .5, KOUNT = 400000
PREPAR T,PPZR,YPSY,EEHTRS
```

```
OUTPUT
T,WCPI,PPZR,WPSG,POWER,PSTO,WFWI,YXC,ZLLPZR,'NCIOUT'=200
START
SET CALPLT=.T.,GRDCPL=.F.,SYMCPL=.T.,NPCCPL=50,TTLCPL=.T.
SET XINCPL=5.,YINCPL=5.
SET TITLE ="              LOFT/ACSL SIMULATOR"
PLOT 'XAXIS'=T,'XTAG'='(SEC)','XLO'=0.,'XHI'=750.,PPZR ,...
   'TAG'='(PSI)','LO'=2000. ,'HI'=2500.,'CHAR'='*'
PLOT 'XAXIS'=T,'XTAG'='(SEC)','XLO'=0.,'XHI'=750.,YPSY, ...
   'TAG'='(  OPEN)','LO'=0. ,'HI'=1.5,'CHAR'='*'
PLOT 'XAXIS'=T,'XTAG'='(SEC)','XLO'=0.,'XHI'=750.,EEHTRS,...
   'TAG'='(KW)','LO'=000. ,'HI'=60.  ,'CHAR'='*'
SET NDBUG = 1
CONTIN
SAVE 'IC'
SPARE$CONTIN$SPARE
STOP
PROCED RUN
RESTOR 'IC'
REINIT
SET ZZTICG = 0.
SAVE 'IC'
SET TRANS = .TRUE.      ,IALG=2
SET KOUNT = 6000000 , NDBUG = 1 , TSTOP=20.   ,CINT=.05
PREPAR ZTIME,RSGPRS,...
   PSTO,WSGO,RFLOW,RLEVEL,ZLLPZR,PCPI,RCLPRS
OUTPUT T,PSTO,WCPI,WPSG,POWER,YBRK, ...
   WFWI,WHPI,ZLLPZR,'NCIOUT'=40
START
RANGE 'ALL'
SET CALPLT=.T.,GRDCPL=.F.,SYMCPL=.T.,NPCCPL=50,TTLCPL=.T.
SET XINCPL=5.,YINCPL=5.
SET TITLE ="              LOFT/ACSL SIMULATOR"
PLOT
'XAXIS'=ZTIME,'XTAG'='(SEC)','XLO'=0.,'XHI'=200.,ZLLPZR,...
   'TAG'='(PSI)','LO'=00. ,'HI'=6.,'CHAR'='*',RLEVEL,...
        'CHAR'='@','SAME','OVER'
PLOT
'XAXIS'=ZTIME,'XTAG'='(SEC)','XLO'=0.,'XHI'=200.,WSGO,...
   'TAG'='(PSI)','LO'=00. ,'HI'=6.,'CHAR'='*',RFLOW,...
        'CHAR'='@','SAME','OVER'
PLOT
'XAXIS'=ZTIME,'XTAG'='(SEC)','XLO'=0.,'XHI'=200.,PSTO,...
   'TAG'='(PSI)','LO'=00. ,'HI'=6.,'CHAR'='*',RSGPRS,...
        'CHAR'='@','SAME','OVER'
PLOT
'XAXIS'=ZTIME,'XTAG'='(SEC)','XLO'=0.,'XHI'=200.,PCPI,...
   'TAG'='(PSI)','LO'=00. ,'HI'=6.,'CHAR'='*',RCLPRS,...
        'CHAR'='@','SAME','OVER'
SET NDBUG=1
SAVE 'CONT'
CONTIN
STOP
```

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